GEOLOGICAL ASPECTS OF PLANNING ARTIFICIAL ISLANDS OFFSHORE TEL AVIV, ISRAEL

by

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1. INTRODUCTION

1.1. General background

Israel is developing into one of the most densely populated countries in the western world. Israel's area within its 1967 borders (excluding the West Bank and the Golan Heights) is 21,500 square kilometers. According to the last published population census, in September 1998 the population within this area numbered 5,987,000 people. The population density of the country is thus 280 people per square kilometer (p/sk, hereafter). However, the Negev district, in the southern part of the country, which occupies about 65% of the country's area, is very sparsely populated. At present its population density is 34 p/sk. Most of the population is concentrated in the rest of the country. In this part the average population density is currently about 600 p/sk. This density is 85% higher than in Belgium and Japan (325 p/sk), and 60% higher than in the Netherlands (375 p/sk), which are the densest countries in the Western world. Moreover, Israel has the highest rate of population growth among developed countries. In the last 20 years the average rate of population growth was close to 3%, about three times higher than in other developed countries. This high rate is due to a relative high rate of natural population growth, and a high rate of immigration. It is estimated that in the next 25 years the population will continue to grow at an annual rate of 2%, compared with an estimated rate of only 0.4% in other developed countries, reaching 8.7 million people in the year 2020. By this year population densities will reach 400 p/sk for the entire country, with 860 p/sk in the northern part, and 44 p/sk in the south (Mazor et al., 1997, p.16).

The expected population growth would exert an ever-increasing demand on land, which is already in short supply. The cumulative effect on the demand for land can be expected to be substantially higher than would seem from the demographic figures alone. This is so because according to the prevailing trends in developed countries, the number of individual household units is expected to grow at a faster rate than the rate of population growth. This trend is due, among other things, to the decline in the number of marriages, the increase in divorces, and the tendency of young people to establish independent households earlier than before. Moreover, because of the constant increase in the standard of leaving and the demand for more spacious leaving quarters, the average area and size of the housing units is expected to rise as well. The demand for land is of course not limited to housing for dwellings. Increased demand will also arise for commercial and industrial use, office space, power plants, tourism, recreation, roads, and infrastructure systems.

The high population density and shortage of land situation are most acute along the Mediterranean coastal plain where about 70% of the country's population is concentrated in urban communities. The coastal belt has an average density of 1,200 p/sk. The city of Tel Aviv is located in the center of this belt. It is the principal commercial, business and cultural center of the country. At present the population in the Tel Aviv metropolitan area numbers 2.6 million people, the population density is 6720 p/sk, and its population growth rate is 2.3% per year. In the Tel Aviv metropolitan area one thus finds the greatest demand for land resources facing the greatest shortage. This is all the more so with regard to seaside land of which there are no tracts left at all.

The city of Tel Aviv has another acute problem in Sde Dov, the municipal airport that is located in the middle of a residential area in the northern part of the town (Fig. 1.1). The airport traffic is an environmental nuisance and a safety threat to its immediate neighborhood. Furthermore, the airfield occupies most valuable tracts of land, and the air traffic space which it occupies prevents the construction of high rise buildings for miles around it. The airfield obstructs the development of a much needed main traffic artery and, altogether, disrupts the functional integrity of the urban fabric.

This situation, which will only get worse with time, has prompted several entrepreneurs, architects, and urban planners to propose the construction of artificial islands offshore Tel Aviv as a possible solution to the land shortage in general, and the high and growing demand for seaside land in particular. In view of the extremely high land prices it appears that artificial islands could become an economic viable alternative to land onshore. The only sensible alternative location for the municipal airport, which should preferably be close to the town's center, is an offshore island. An airfield at sea solves the three most acute problems of safety, noise, and building restrictions. Indeed, the relocation of the airport to the sea has been seriously considered already in 1973, but the idea was discarded for various essentially non-substantive reasons. *

An initial feasibility study concerning some aspects of the islands' construction was carried out from 1993 to 1995 by a team from the Faculty of Civil Engineering of the Technion, Haifa, Israel, and Lievense Consulting Engineers of Breda, The Netherlands (Shelef et al., 1994; Zimmels and Shelef, 1996). Following this study and further negotiations between the governments of The Netherlands and Israel, the two countries signed in January 1996 a memorandum of understanding for cooperation in promoting coastal engineering research in Israel. It was agreed that its implementation will start with a comprehensive feasibility study regarding marine land reclamation offshore the Mediterranean coast of Israel by building artificial islands. Each government contributed one million US Dollars to the project. A joint steering committee was established in order to implement the project.

The steering committee decided that at this stage the feasibility study should concentrate on an evaluation of several alternative design schemes of residential islands and an airport island offshore metropolitan Tel Aviv (Figs. 1.1, 1.2). The committee defined the following issues as the main tasks of the project: (1) Assessment of the effects of the island on the coastal environment and the beaches. (2) Determination of the availability of suitable fill materials in the offshore, their quantity, cost of extraction, and the possible adverse environmental effects that may arise from their mining or dredging. The work plan also included the investigation of several other factors that should be taken into account in planning the islands, such as seismic risk, economic aspects, land use, marine engineering, and legal aspects. The work on the program began in July 1, 1997 and it is scheduled to be completed by the end of July 1999.

* The distinction between a residential island and an airport island, from a technical standpoint, is as follows:

The plan for the airport island is shown in Figure 3.2. As described in the text (p. 2), it is to replace Tel Aviv's municipal airport. Its dimensions and layout (a rectangle 2,900 m. by 800 m.) were specified by the Civil Aviation Authority. These specifications are quite rigid and, as far as first order planning considerations are concerned, the only 'degrees of freedom' left are its distance from shore and exact geographical location.

The residential island is meant to accommodate high rise apartment buildings. Its size, design and layout are flexible. The decision to consider just one such island is arbitrary. The simulation runs reviewed in Chapter 3, along with some other cost/benefit considerations, established that a drop-shaped island, with an area of two square kilometers, positioned 1,000 m. from the shore, would be the best overall solution. This solution is displayed in figures 1.1 and 3.1. The intention to limit land use to residential buildings, which is embodied in them, grew out of the realization that apparently only high rise apartments buildings may turn the investment into a profitable enterprise.

There is, however, also another angle to the distinction between the two types of islands that is related to the very attributes of each type. The entire idea of building artificial islands opposite Tel Aviv will undoubtedly be met with fierce opposition from environmental groups and other interested parties. The genuine need and justification for an airport island is far more obvious than for a residential one. An airport island will be a national project, financed and maintained by government funds. The public at large will be much more confident that all the necessary precautions will be taken to prevent the forcasted adverse environmental impacts. The opposite is probably true in the case of the residential island, which will be a private enterprise. These considerations will be aired in debate, if and when the project will be seriously considered.

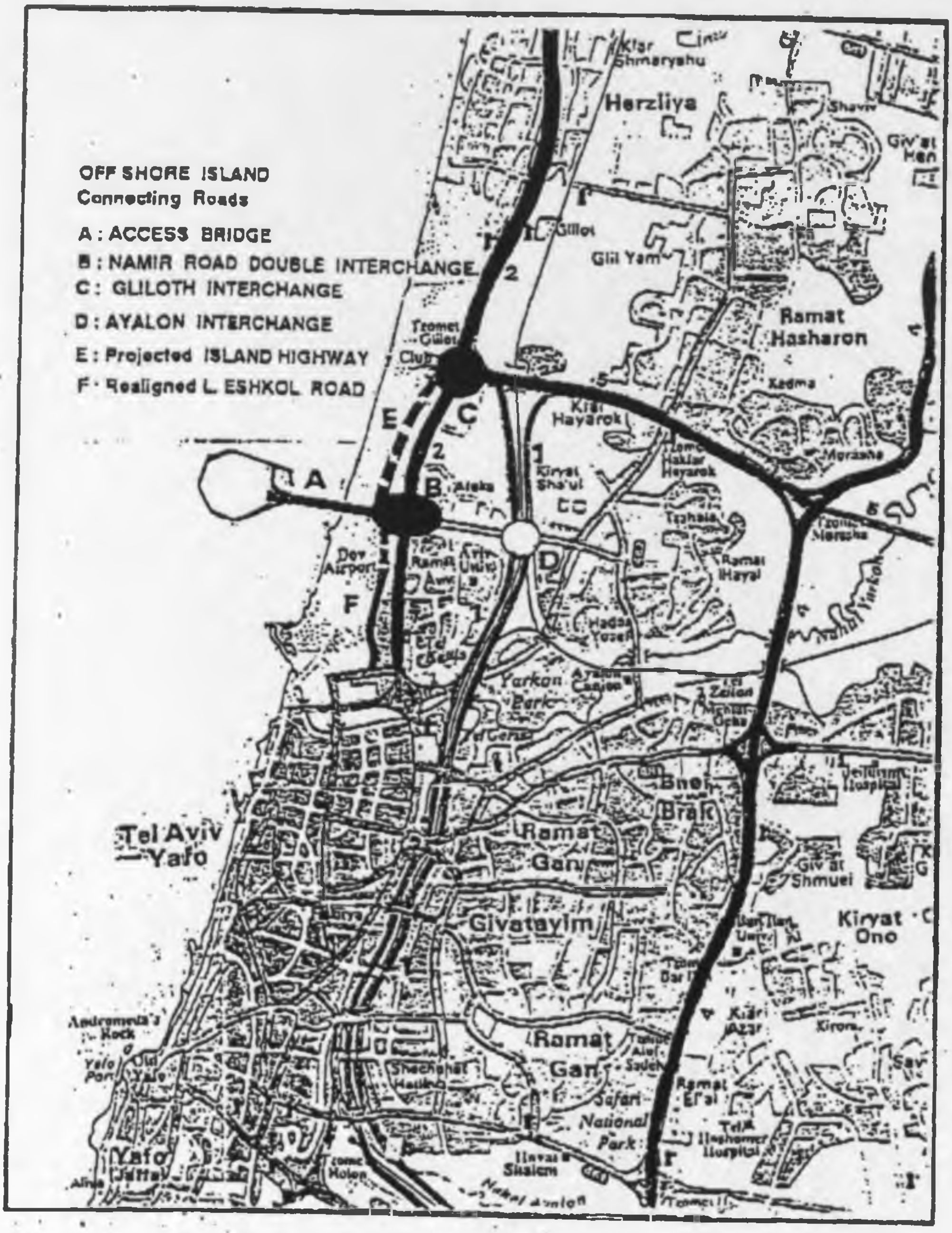

Figure 1.1. Metropolitan Tel Aviv area, principal transportation arteries, and the proposed location and layout of the drop-shaped residential artificial island, 1000 m offshore the northern part of the city. Note the situation of the Dov municipal airport (south of the island's connecting bridge), in the middle of the northern residential suburbs of Tel Aviv (from Shelef et al., 1994).

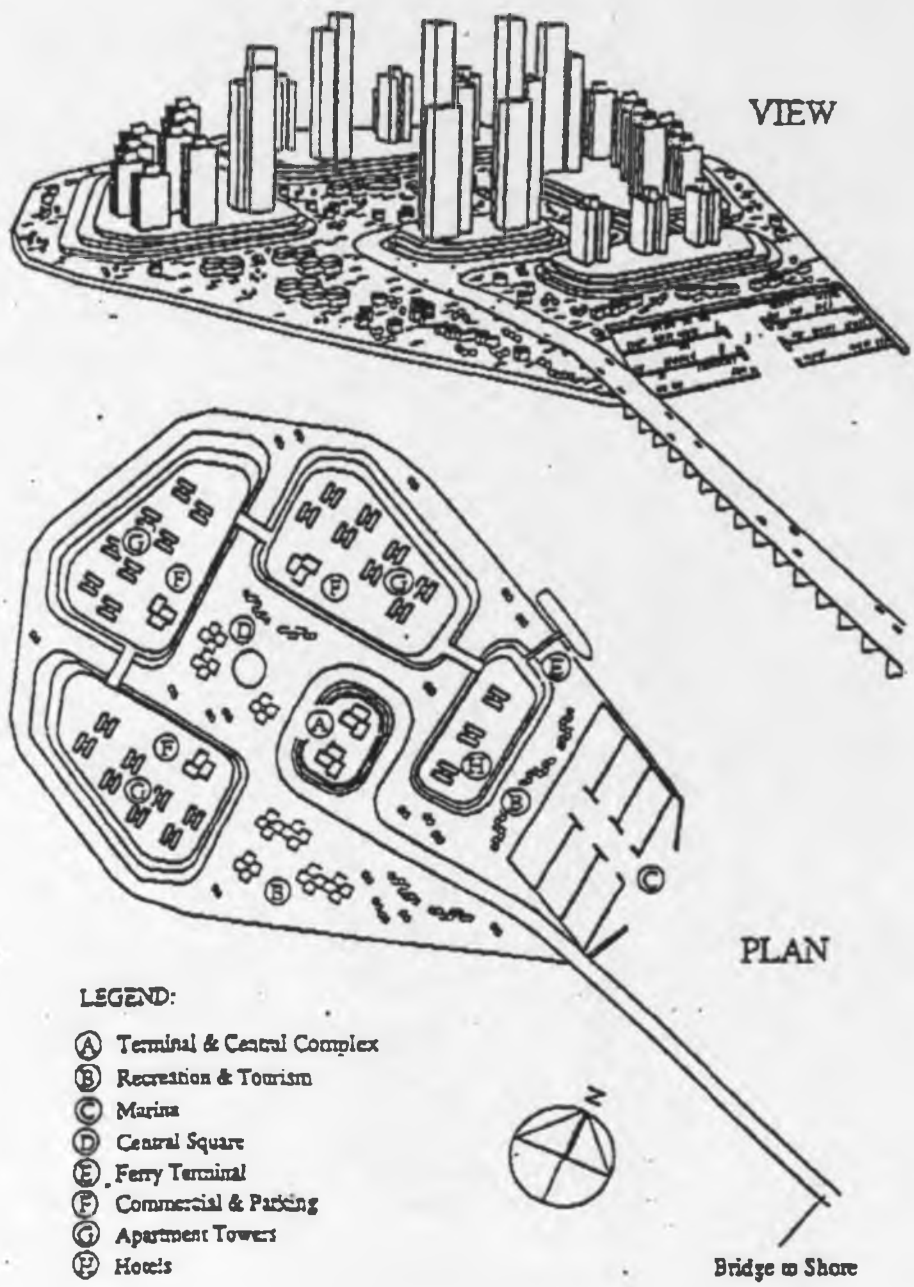

Figure 1.2. Architect M. Wertheim's conceptual site plan for a 1000 dunams (250 acres) residential artificial island (from Shelef and Zimmels, 1995).

1.2. Scope and objectives

In this report I discuss several aspects of planning artificial islands offshore Tel Aviv that are related to the local geological and sedimentological situation.

The first subject (Chapter 2) is a review of the sedimentological conditions and the overall sand balance in Israel's littoral zone. This evaluation is necessary in order to understand and assess the environmental effects of the artificial islands.

The second topic (Chapter 3) is an assessment of the adverse effects that an island may have on the coastal environment, and the measures that should be taken to rectify these impacts. The assessment is based on the results of the numerical simulations obtained by the Dutch team that investigated this question under the framework of the joint Israeli-Dutch feasibility study.

The third subject (Chapter 4) involves the determination of the availability of suitable fill materials in the offshore, their quantity, cost of extraction, and the possible adverse environmental effects that may arise from their mining or dredging. The Geological Survey of Israel (GSI) and Israel Oceanographic & Limnological Research Ltd. (IOLR) were contracted by the project to carry out the survey for marine fill materials. In my capacity as a geologist with the GSI, I was actively involved in carrying out this task. The work of our team was summarized in several technical reports (Almagor, Gill and Hall, 1997; Almagor, Gill and Perath, 1998; Golik, Gardosh, Gill and Almagor, 1998; Gill and Almagor, 1999; Almagor, Gill and Golik, 1999; and Golik, Gardosh, Gill and Almagor, 1999). In the present report I present a summary of my own and our team's work on this topic.

The forth subject (Chapter 5), is an assessment of the seismic hazard that islands offshore Tel Aviv may face, and the measures that should be implemented to minimize the potential damages of earthquakes. This chapter is based on a review of the lessons learned from the Japanese artificial islands that experienced a severe earthquake, and on my synthesis of the local seismic hazard.

2. SEDIMENTARY DYNAMICS OF ISRAEL'S LITTORAL ZONE

This chapter presents a review of the main sedimentary processes that take place in Israel's coastal zone, and an evaluation of the overall coastal sand balance. This review provides important background information for the discussions in chapters 3 and 4.

2.1. General sedimentological setting – the Nile littoral cell

Israel's littoral zone is the northern part of the Nile's littoral cell which extends from the Nile Delta in Egypt to 'Akko at the northern tip of Haifa Bay, Israel, a distance of some 650 km (Fig. 2.1). Clastic sediments (quartz sands, silts and clays) derived from the Nile River and its delta have been accreting on the inner shelf of northern Sinai and Israel at least since the Pliocne (5 million years before present). The transportation of the sediments is controlled primarily by the longshore currents that prevail in the southeastern Mediterranean. The longshore currents are the result of wind-generated waves that break at an angle to the shoreline, thereby causing flow along a narrow nearshore zone. The currents reach down to a depth of 6-7 m, some 300-350 m offshore (Golik *et al.*, 1996). The waves in the southeastern Mediterranean are generated by the prevailing wind fetch (N260-280°E azimuth) from the Sicilian Channel, 2,400 km west of Israel's coast. The direction and magnitude of the longshore current are determined by the angle of incidence at which the wave fronts meet the coast, and by the wave energy. Changes in angle between the impinging wave fronts and the broadly concave coastline of northern Sinai and Israel cause a gradual northward decline in magnitude of the longshore currents along Israel's shore (Emery and Neev, 1960). North of Netanya, the angle of wave impingement on the shore may generates a southward flowing current during the summer months when winds blow from the northwest direction (Goldsmith and Golik, 1980). The long-term net sand transport is, however, directed northward, owing to the stronger longshore currents generated by the winter storms which are directed primarily from the southwest.

Since the construction the Aswan dams (the Low Dam in 1902 and particularly the High Dam in 1964) the Nile Delta has ceased growing, and it undergoes marine erosion. The sediments eroded from the Nile Delta by storm waves offshore Egypt are transported along the shores of northern Sinai and Israel by the longshore current. The net annual longshore sand transport in different coastal segments within the Nile's littoral cell have been estimated by several authors using different estimation techniques and numerical modeling schemes. These include estimates based on measurement of sand accumulation behind manmade coastal structures (breakwaters, etc.), tracer experiments, and computations according to several theoretical models of wave-induced energy flux. Rosen (1998) presents a comprehensive review of all the previous studies. The various estimates are summarized in Figure 2.1. The volume of sediment transported by the longshore current decreases from 800,000 m^3 at the Nile's mouths, to 100,000 m^3 opposite the Carmel promontory, south of Haifa Bay. The longshore sand transport terminates in Haifa Bay. Some of the sands settle within the bay and part of the sand is dispersed seaward through submarine canyons.

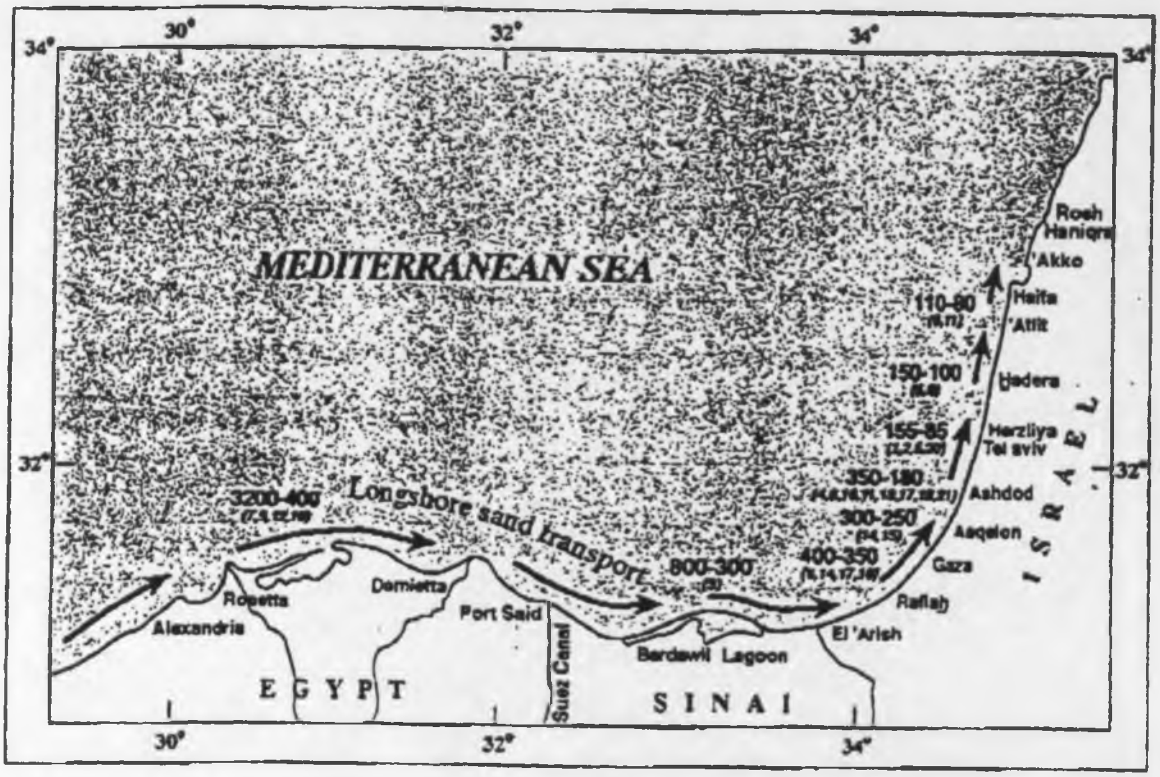

Figure 2.1. Annual volumes, in thousand cubic meters, of longshore sand transport in the Nile littoral cell. This figure also serves as a reference map to the towns along the Mediterranean coast of Israel that are referred to in the text.

2.2. The negative sand balance in the nearshore zone

A sand balance evaluation is an accounting exercise that attempts to take stock of the volumetric gains and losses of sediments that are transported into and out of a coastal compartment over a given time period. Unraveling the coastal sand balance facilitates a proper understanding and a more quantitative formulation of coastal processes. In particular, it enables to investigate and assess the relative importance of the different agents that control coastal processes. Such an insight is instrumental to formulating optimal coastal management policies.

The sand balance in a coastal compartment is the difference between the volume of sand added to it (gains), and the volume that is withdrawn from it (losses). Theoretically, the balance should be indicative of the state of the coast. When the difference is nil, the shoreline is stable. If positive, coastal accretion takes place and wider beaches are formed. A negative balance will result in coastal erosion leading to landward shoreline retreat, narrowing beaches, and erosion and retreat of backshore coastal cliffs.

2.2.1. Evidence for the prevalence of a negative sand balance

The following phenomena attest to the fact that the sand balance is negative:

(1) *Direct evidence for long-term shoreline retreat*

Nir (1989), comparing aerial photographs taken over a period of 40 years since 1949, found evidence for shoreline retreat from Palmahim northward, increasing from 10 m south of Tel Aviv to 15 m along the Netanya-'Atlit shoreline, to at least 25 m along the Carmel coast. Along some coastal stretches (Gaza-Ashdod and Tel Aviv-Netanya), the shoreline has remained stable, whereas in the south, the Rafiah-Gaza coast has widened by an average of 20 m. New studies of shoreline migration confirm that considerable retreat has taken place at several localities between the 1950's and the 1980's (Rosen, 1992). These conclusion are substantiated by many first hand eyewitness testimonies about narrowing beaches and submergence of once above-water objects by individuals who are familiar with the coast.

(2) *Backshore cliff retreat*

The landward migration of the backshore kurkar cliff, estimated to be on the order of 15-25 cm/y in recent years (Perath and Almagor, 1996), provides direct evidence for shoreline retreat. Since the kurkar rocks in the Sharon escarpment are readily abraded, the erosive notch at the base of the kurkar cliffs, which initiates the erosive cycle, marks the maximal landward reach of the wave swash. Therefore, the progressive retreat of the cliff-line indicates that the sea is continuously advancing inland. This process may be due to an eustatic sea level rise, which however is not supported by direct measurements, or to coastal erosion, which seems to be the more likely cause.

(3) *No realization of beach accretion potential*

Due to the concavity of the coastline and the consequent progressive northward decrease in the angle of incidence of the approaching waves, the energy flux and sediment-carrying capacity of the wave-induced longshore current is gradually reduced northward. Consequently, every coastal segment actually receives from the south more sediment than it releases to the north. This discrepancy should have conceivably led to long-term beach accretion all along the coast, a process that evidently does not take place, even not locally (except where sand is trapped by manmade structures). The lack of accretion can be due to: (a) The longshore supply falls short of the theoretical volume because sediment is blocked upstream by manmade structures, or because the theoretical amount is not available to begin with. (b) The surplus is swept out of the system to the offshore or to the land. (c) A rise in sea level that creates new accommodation space such that nearshore deposition takes place while the shoreline remains unchanged. It should be noted that in a coastal compartment a 100 km long and 2.5 km wide, a 1 mm rise in sea level per year creates new accommodation space of 250,000 cubic meters. However, this possibility seems to be contradicted by observations that the nearshore zone experiences removal rather than addition of sediments (see (4) below), and should, therefore, be discarded..

(4) *Recent uncovering of offshore archaeological remains*

A deficit in sand supply at any segment of the coast will cause the remobilization and sweeping away of sediments that underlie the surf zone. That this process does occur is indicated by the recent exposure of archaeological remains which, until just a few years ago, were still covered by a protective veneer of sediments (e.g. the Atlit-Yam Neolithic settlement; a Phoenician merchant vessel opposite Ma'agan Michael; many finds from various periods offshore Ashqelon). Seabottom erosion is further indicated by the recent uncovering on the sea floor of clay and kurkar layers which only 30 years ago were covered by a 2 to 5 m thick layer of sand. Since these are very recent phenomena they are most likely a consequence of the deficit created by the manmade structures.

2.2.2. Causes for the negative balance

The sand balance, and its consequences in terms of the coastal response, is affected by human action and by the natural processes that operate along the coast. It appears that in the case of the Israeli coast both of these factors operate in a way that causes a shortage of sand along the coast.

2.2.2.1. Sand shortage due to human actions

The mining of sand and the construction of coastal structures have been the predominant reasons for the shortage of sand in the nearshore zone. It is estimated that until 1964, when beach sand mining was outlawed, some 10 million cubic meters of sand have been mined from Israel's beaches (Neev *et al.*, 1963). The uncontrolled mining caused beach narrowing and seasonal sand stripping. Some of the damaged beaches have not yet recovered.

Man-made marine structures intercept the longshore sand transport, causing sand accumulation on the upstream side of the structure, and beach erosion in the downstream direction. Fifty-five seaward-projecting and offshore structures, including harbors, marinas, groins, and detached breakwaters, were already in existence in 1989 (Nir, 1989). Since then a number of major structures have been added, including the Gaza harbor, the Ashqelon power plant's coal terminal, and the marinas at Ashqelon, Ashdod and Herzliya. Golik (1997) estimates that about 10 million cubic meters of sands have been entrapped by these structures. The shortage of sand downstream (north) of the structures have caused shoreline retreats of 15-25 m along stretches that extend 1,500-2,000 m to the north of the structures.

The amount of sand that has been withdrawn from the coastal system due to human action sums up to 20 million cubic meters. The natural inflow of sands at Gaza amounts only to about 400,000 cubic meters per year. Thus, the manmade deficit, which is equivalent to 50 years of natural supply, is a dominant cause for the shortage of sands in the coastal system.

2.2.2.2. Sand shortage due to natural processes

The following observations indicate that sand is transported out of the nearshore compartment into deeper water by natural processes:

1. *Distribution and offshore extent of Recent sand deposition*

The Israeli coast is skirted by a sand belt that is 2.5-4 km wide. High-energy winnowing in the surf zone removes the fine fráction and transport the well-sorted clean quartz sands to water depths of 15-25 m, the approximate wave base (Emery and Neev, 1960; Nir, 1973, 1984). Along considerably long stretches the seaward boundary of the sand belt is determined by a linear small ridge on the seafloor that acts as a dam to the further seaward transport of sands. At water depths greater than 15-25 m the sand is increasingly mixed with fine-grained sediments (25-90% silt and clay).

2. *Steep foreshore seabed profile*

The shore-perpendicular sea-floor profiles all along the coast up to Haifa Bay typically consist of two sections of different slopes. From the shoreline to a depth of 30 m, some 2.5-4 km offshore, the seabed slopes at an angle of about one degree. The nearshore incline ends at a nickpoint beyond which the seabed is practically flat. The nearshore incline is steeper than the theoretical equilibrium slope which can be expected for the median grain size diameter in this zone (0.1-0.3 mm) (see Komar, 1976, p.303-308; Charlier and De Meyer, 1998, p.127). This indicates that the slope is not in equilibrium, and that substantial amounts of sand can still be added to this zone before its slope will be reduced to the theoretical equilibrium slope. As mentioned above, the surficial sediments in this zone consist of sand-sized material, indicating that it does receive an influx of sands from the coastal system. Seaward sand transport from the coastal zone is affected by shore-perpendicular wave motion which moves sands out of the breakers zone into deeper water (*e.g.* Komar, 1976, Chapter 11). In contrast, west of the nickpoint, the slope of the sea floor is almost flat, and the surficial sediments consist mostly of silt and clay. Thus, this zone lies beyond the active coastal sedimentation zone.

The natural dynamic process strives to adjust the slope to the more moderate equilibrium profile. In this process sand is withdrawn from the proximity of the coastline and is being deposited down the slope. The seaward transport is aided by the steepness of the slope. This process increases the deficit in the coastal sand balance and enhances the erosion of the coast.

These observations have immediate implications concerning the mining of sand in the nearshore zone. Withdrawal of sands from this zone will be compensated by withdrawing an equivalent volume of sand from the coastal system, which will, in turn, increase the risk of coastal erosion. Therefore, the mining of sands from the nearshore sand belt should be disallowed. This recommendation was already adopted by the project's steering committee.

2.2.3. Estimating the amount of seaward transport

The annual amount of sand that escapes out of the coastal compartment to deeper water can be estimated by evaluating the overall sand balance of the entire coastal compartment. The compartment for which the sand balance is evaluated comprises the coastal zone between Gaza and Haifa, encompassing the shore-adjacent belt within which the longshore currents are taking place, and the beach. This compartment can be treated as one unit because within it the long-term net longshore transport is directed northward and the coast behaves uniformly by being for the most part erosional (or at least on the retreat) throughout its extent. Furthermore, this definition allows disregarding the interchange of sand between the submerged shore-adjacent sandy belt and the beach.

The two principal processes that contribute sands to Israel's coastal zone are longshore sand transport (LST_{gain}), and the erosion of the backshore kurkar cliffs (cliff abrasion, *CA*) (Emery and Neev, 1960; Neev *et al.*, 1963). The gains from other sources are insignificant. Sand losses include sand removal by the longshore current (LST_{loss}), by landward eolian transport (*ET*), and by seaward transport (ST). Accordingly, the bulk of the sand balance (*SB*) is expressed by the equation: $SB = (LST_{gain} + CA) - (LST_{loss} + ET + ST)$.

The sand balance evaluation is based on data from the literature. Reasonable estimates exist for all the variables except for seaward sand transport (ST), which, as a matter of fact, has thus far not been recognized as an important process. By assuming a zero difference, the value of *ST* can be estimated. Since there exists strong evidence that the coastal compartment suffers from a negative sand balance, this estimate will be minimal.

The volume of sands that enter the system at Gaza (LST_{gain}) each year is estimated at 350,000-400,000 m^3 (Migniot, 1974; PortConsult, 1987; Delft Hydraulics, 1994;

Bosboom, 1996). The volume of sand leaving the system at the Haifa Bay sink (LST_{loss}) is estimated at 80,000-110,000 m^3 (Migniot, 1974; Carmel *et al.*, 1984; 1985). Thus, between Gaza and Haifa the longshore current system loses about 300,000 m^3.

The annual volume of sand contributed by the erosion of the backshore cliff (*CA*) was estimated at 180,000-260,000 m^3 by Perath (1982). In the present evaluation, 200,000 m^3 is used as a reasonable estimate for this gain. The annual volume of sand removed from the coastal system by wind to inland dunes has been estimated by Goldsmith *et al.* (1990) at about 42,000 m^3.

Thus, in crude and rounded figures, the known annual gains and losses amount to 600,000 m^3 (LST_{gain} = 400,000 m^3, CA = 200,000 m^3) and 150,000 m^3, (LST_{loss} = 100,000 m^3, ET = 50,000 m^3) respectively. Since there is no evidence for coastal accretion, a volume of at least 450,000 (± 375,000) m^3 must therefore be attributed to seaward transport.

This figure provides approximate bounds for the annual volume of seaward transport. It is emphasized that all the volumes used in this evaluation are estimates that inherently embody a significant margin of error, hence the large value of the error term. Furthermore, it should be appreciated that the volumes attributed to the longshore transport pertain to the theoretical carrying capacity of the longshore current, and not to the actual volumes that are transported. Hence, if the actual amounts are substantially smaller than the theoretical ones, the value of ST will change accordingly.

3. ANALYSIS OF COASTAL ENVIRONMENTAL EFFECTS

3.1. Objectives

The objective of this chapter is to present an assessment of the long term adverse effects that the island may have on the coastal environment, to indicate the maintenance measures that should be taken to rectify these negative impacts, and provide a rough estimate of the long term costs of the maintenance operations.

The principle concern arises from the fact that artificial offshore structures interfere directly with the natural wave and current climate. This interference affects the longshore sediment transport and disrupts the sediment supply and the natural sediment balance in the nearshore zone and along the coast. Specifically, an artificial island acts as a detached breakwater. Such structures tend to impede the natural free flow of sediments in the nearshore zone, causing sediments to accumulate between the structures and the shore. This creates a deficit of sediment on the downstream side, which in turn leads to coastal erosion and landward shoreline recession.

The environmental impacts of artificial islands can be evaluated by numerical modeling. The modeling tools provide the means to simulate the impact of different island design schemes and investigate the effects of individual design parameters, like the island's shape and size, or its distance from shore. The simulation results facilitate the identification of the least harmful design scheme from an environmental standpoint, and the formulation of remedies to mitigate the forecasted adverse environmental impacts. The assessment is based on the results of the numerical simulations obtained by the Dutch team that investigated this question under the framework of the joint Israeli-Dutch feasibility study.

The most common remedies are artificial sand bypassing and beach nourishment. The modeling serves to provide quantitative estimates of the long-term effects of the islands and the volumes of sediments that will have to be mobilized artificially. These, among other things, can then be translated to economic costs which are crucial to the overall evaluation of the costs and benefits of the endeavor.

3.2. Assessment procedure and results

The simulations were performed by the Dutch firm Delft Hydraulic (WL/Delft Hydraulic, 1998). The modeling is done in two steps. In the first step the models simulate the effects of the structures on the wave approach pattern and energy. The modified wave information is then used as input to the sediment transport model.

The modeling was carried out for a 50 km long part of the coast, extending 25 km on either side of the proposed site, between Palmakhim in the south and Bet Yanay in the north. The simulations programs utilize the following sets of data:

(a) Sea bottom topography.

(b) Schematized characteristic meteorological data on wind climate and oceanographic data on tide, wave, and current climate. These data were generated by a special algorithm that condenses the measurements acquired by the Israel Oceanographic and Limnological Research Institute in Ashdod and Haifa over many years into a reduced set of representative data. This process involves inevitable simplifications and generalizations.

(c) Sedimentological data about the longshore sediment transport in this sector of the coast. The volumes used were an input of 140,000 m^3/y at the southern end of the area and an outflow of 25,000 m^3/y at the northern end. This model represents a loss of about 3 m^3/y for every kilometer along the coast. Some material is lost to the deeper offshore due to the steep foreshore slope and some is blown inland by the wind. In general, this represents a quantification of the negative sand balance situation which has been elaborated upon in Chapter 2.

(d) The physical attributes of the island in question. This includes its geographic location, which prescribes its distance from shore and the local bottom topography, and its shape and physical dimensions.

The computer program generates plots, graphs and reports that summarize the following impacts:

- The development of a salient (tombolo), the accretion of the beach, or coastal advance seaward, "in the shadow" of the island, between the island and the coast.
- Maximal coastal retreat (perpendicular to shoreline) north of the island.
- Length over which significant coastal retreat north of the island will occur.
- Maximal coastal retreat (perpendicular to shoreline) south of the island.
- Length over which significant coastal retreat south of the island will occur.

These impacts are evaluated for 10, 50, and 100 years after the construction of the island.

Each simulation run addresses a specific island layout. The practice is to change the value of a certain parameter, like the distance from shore, and observe the impact of this change. In this fashion it is possible to investigate the impact of individual design and location parameters and devise an optimal solution.

For the purposes of this project many different island configurations were tested. The design parameters that were tested for the residential island were:

(a) <u>Island's shape</u>: the tested shapes included rectangles, squares, circles, ellipses, and drop shaped islands. It was found that the drop shaped island is the preferred shape and this shape featured in all the subsequent tests.

(b) <u>Island's distance from shore</u>: distances of 1,000, 1,750, and 2,500 meters were tested. The simulations reveal that the further away the island is located from the coast the greater the distance to the north of the island over which coastal erosion takes place.

However, in addition to weighing the sedimentological impacts, the preferred solution has to balance the cost benefits arising from building the island in shallow water close to shore (i.e. substantial less fill material and a shorter bridge) against the penalty of a negative visual impact, which worsens as the island is located closer to shore.

(c) Island size: schemes of 1,000, 2,000, and 5,000 dunams (1 dunam = 1,000 square meters; one quarter acre) drop shaped islands were tested. A size of 1,000 dunams is the minimal size worth considering. The estimates of the cost of construction per meter of island showed a significant drop when the size is doubled from 1,000 dunams to 2,000 dunams. Increasing the island to 5,000 dunams does not reduce the cost much further. On the other hand, the environmental impacts of a 5,000 dunam island are much more severe.

After testing the various alternatives discussed above it was determined that a 2,000 dunam island located 1,000 m from shore is the best solution (Fig. 3.1).

The impacts of such an island on the coast morphology after 10, 50, and 100 years are summarized below.

Impact after (years) :	10	50	100
Shoreline advance (m) behind island	210	400	460
Maximum retreat of coast north of island (m)	70	120	130
Length over which coastal erosion occurs north of island (km)	6	11	14
Maximum retreat of coast south of island (m)	28	21	12

After 100 years the estimated cumulative volumes of sediment that will be involved in the various parts of the affected coast are as follows:

(a) The tombolo between the shore and the island will accumulate 9 million cubic meters of sediments.
(b) 30 million cubic meters of sand will be eroded from shores and beaches north of the island.
(c) 0.5 million cubic meters of sand will be eroded from shores and beaches south of the island.

Thus, altogether, to prevent the adverse effects outlined above, over the said 100 years, it will be necessary to dredge 10 million m^3 of sand to prevent the development of the tombolo, and nourish the beaches to the north of the island with 30 million m^3 of sand to prevent their erosion. The long term maintenance operations will thus require moving 400,000 m^3 of sand per year, 300,000 of which will have to be supplied from an outside source. These costs have to be taken into consideration while evaluating the cost of the project.

The airport island is a 2,900 m long and 800 m wide rectangle. Two positions were tested, 1,250 m and 2,500 m away from the coast (Fig. 3.2). At 1,250 m from the coast

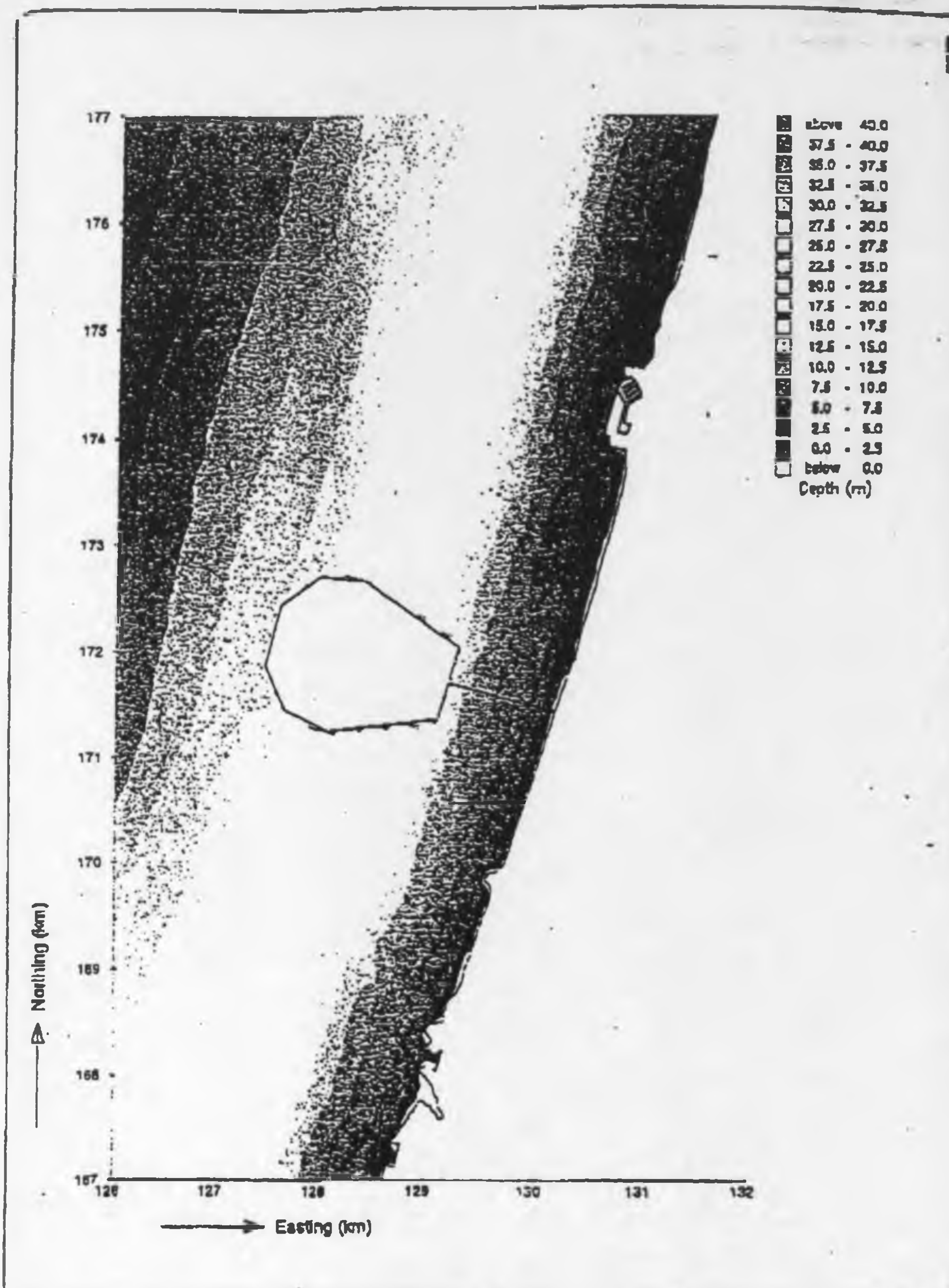

Figure 3.1. Proposed layout for a 2000 dunams (500 acres) drop-shaped residential island, whose eastern edge is situated 1000 m offshore, opposite the Tel Baruch suburb in northern Tel Aviv (scale 1:50,000; WL/Delf Hydraulics, 1998, fig. 7).

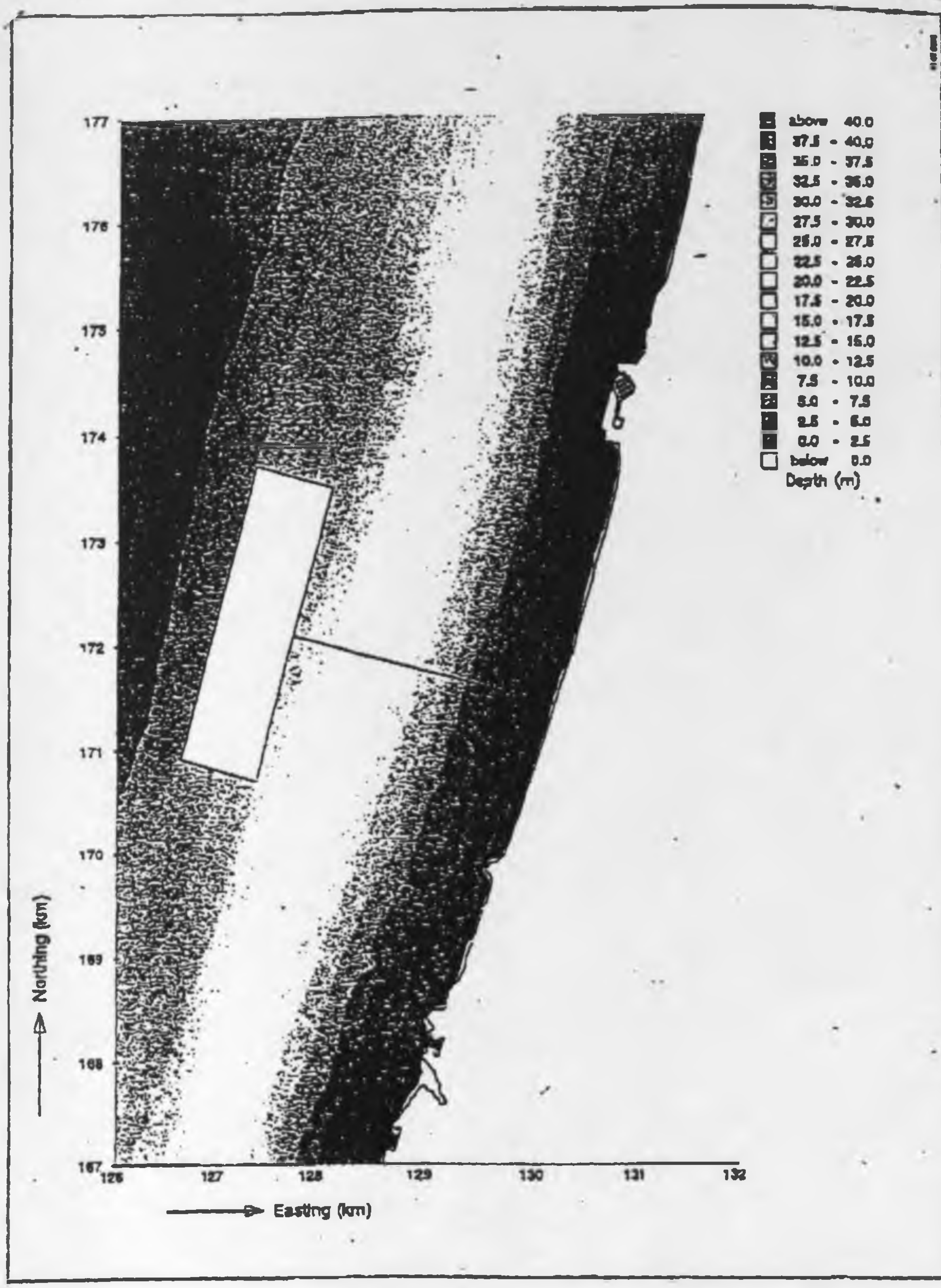

Figure 3.2. Proposed layout for a 2,900 m x 800 m square airport island, situated 2,500 m offshore opposite the Tel Baruch suburb in northern Tel Aviv (scale 1:50,000; WL/Delf Hydraulics, 1998, fig. 15).

the island causes a complete blockage of the longshore transport and within 50 years the shoreline will advance as far as the island, and the retreat of the coast north of the island will be 300 m. At 2,500 m from the coast the impacts are still quite substantial: the shoreline opposite the island will advance by 250, 500, and 800 m after 10, 50, and 100 years, respectively. After 100 years, a stretch of 20 km of coast to the north of the island will have suffered erosion, and the maximal coastal retreat will reach 250 m.

The impacts of the airport island are much more severe than the impacts of the 2,000 dunams residential island. The expenditure on routine long term maintenance operations of removing the tombolo accumulation and beach nourishment will accordingly be close to twice the expenses required for the residential island.

4. AVAILABILITY OF MARINE AGGREGATE RESOURCES FOR ISLAND FILL MATERIAL

4.1. Introduction

At present the only proven method for constructing large artificial islands is the conventional method of building sea walls and filling the space between them with granular aggregates of crushed rocks or loose sands. This technology is the solution which is currently contemplated for the artificial islands in Israel as well. As mentioned above, the residential island and the airport island will require some 70 and 90 million cubic meters of fill material, respectively. The availability and timely supply of sufficient amounts of adequate fill material and its cost at the island's site thus become some of the most important factors that determine the mere feasibility and economic viability of the project.

It should be clarified at the outset that the project cannot count on obtaining fill material from on-shore sources in Israel. At present, Israel does not have sufficient reserves of aggregates for its building and construction industries from on land sources for more than a few years. This has recently become very clear following a comprehensive evaluation of the problems and prospects of the future supply of aggregates, conducted by a special inter-ministerial committee appointed to investigate the issue (Inter-ministerial committee for sand supplies, 1999). A possible alternative could be the importation of aggregates from Jordan or Egypt. However, the logistic and political complications of implementing this eventuality are as yet unclear. Furthermore, according to preliminary estimates, the cost of importing and transporting the aggregates to the island's site may reach 15-17 US$ per cubic meter. This is three times higher than the estimated cost of dredging sands from the offshore (at an estimated cost of 5 US$ per cubic meter), provided of course that adequate reserves do exist there. This background information serves to clarify why the issue of the availability of marine aggregates offshore Israel was singled out by the steering committee of the project as one of the two most important subjects to be investigated at the outset of evaluating the overall feasibility of the idea.

4.2. Constraints on offshore resources of fill material

In the overall context of the project, the local offshore resources of fill material have to comply with the following constraints:

(1) It has to possess adequate geotechnical properties. Sands are rated as a suitable hydraulic fill aggregate for harbor structures and artificial islands, because they can be easily dredged and transported by pipelines. Sands readily achieve relative densities higher than 60%, their permeability is sufficient to allow consolidation during the construction stage, and their settlement after construction is usually negligible. Based on geotechnical considerations and to a large extent also on the lessons learned from the damages caused to artificial islands in Japan during the 1995 earthquake in Kobe (see Chapter 5), it is agreed that the best hydraulic fills are well graded (*i.e.* poorly sorted) coarse sands in a wide range of sizes (2.00-4.75 mm), none dominant, with fines constituting less than 10% of plastic silt and clay particles smaller than 0.075 mm. At

these compositions the sands have a high bearing capacity and an optimal resistance to seismic liquefaction, and can be hydraulically poured with low turbidity.

(2) It has to be found in water depths that are shallow enough to be retrieved by existing bottom dredging equipment. This restricts it to water depths shallower than 60 m.

(3) The exploitation of the resource should not cause adverse environmental effects.

(4) It has to have sufficient reserves to meet the needs of the project. As far as the required volumes of fill material are concerned, the preliminary estimates are that each square kilometer of the residential island positioned 1,000 m offshore Tel Aviv (thus spanning water depths of between 9 m and 27 m) will require about 25-35 million cubic meters of fill material (depending on how high its ground surface will be raised above the water level). It appears that a size of 2 square kilometers is an optimal size for the residential island (see Chapter 3). Hence, the residential island will require some 70 million cubic meters of fill material. The airport island, which will have an area of 2.5 square kilometers and will be positioned 2,500 offshore at water depths of 30-40 m (see Chapter 3), will require approximately 90 million cubic meters of fill material. Thus, the two islands will require a total of about 160 million cubic meters of fill material. This is a vast amount of material and its availability and timely supply at an acceptable rate and cost thus become crucial considerations in evaluating the feasibility and economic cost effectiveness of the project.

4.3. The aggregate exploration program

In order to investigate this important question, the project carried out a shallow seismic survey of the Israeli continental shelf, followed by bottom sampling and probing. The objectives of this study were to locate potential aggregate reserves on the sea bottom or at a very shallow depth below the sea bottom, determine their suitability as fill material, define their spatial distribution, thickness and volume, and the thickness of waste overburden that must be removed in order to exploit them.

The exploration program was carried out by the Geological Survey of Israel and the Israel Oceanographic & Limnological Research Ltd. In my capacity as a geologist with the GSI, I was actively involved in carrying out this task. The work of our team was summarized in several technical reports (Almagor, Gill and Hall, 1997; Almagor, Gill and Perath, 1998; Golik, Gardosh, Gill and Almagor, 1998; Gill and Almagor, 1999; Almagor, Gill and Golik, 1999; and Golik, Gardosh, Gill and Almagor, 1999). In the following sections I present a summary of my own and our team's work on this topic.

The geographic boundaries of the seismic survey were determined on the basis of the following considerations:

(a) As discussed in Chapter 2, it is quite clear that Israel's littoral zone suffers from a negative sand balance. Therefore, at an early stage of the feasibility study, it was decided that in order to protect the coastline and the beaches and refrain from aggravating the shortage of sands, the mining of sands from the nearshore sand belt to the nickpoint of the foreshore slope at a water depth of 30 m will be forbidden. As a water depth of 60 m is presently the practical limit for dredging operations, it was decided that the seismic survey would be carried out between water depths of 30 and 60 m. In actuality, the survey was extended to cover the area between water depths of 25 and 70 m.

(b) Due to budgetary constraints, and in the interest of maintaining a reasonable dense coverage, the study area was limited geographically to the offshore area between Hadera in the north and Ziqim in the south. Exploring the southern part of the shelf was preferred because this area is closer to the site proposed for the artificial islands near Tel Aviv.

The seismic survey consisted of 118 shore-perpendicular seismic profiles, ranging in length from 3 to 15 km and spaced one kilometer apart (Fig. 4.1). In addition, six longitudinal and several diagonal profiles were carried out. In all, approximately 1,500 km of seismic profiles were acquired. The survey was performed using a Datasonics CAP-6600 CHIRP sub-bottom profiler. This system can penetrate to a depth of about 35 m, with a vertical resolution of better than 10 cm.

Based on the analysis of the seismic records and on a compilation of data from previous studies of the continental shelf, two prospective targets were singled out for probing, outcrops of the submerged kurkar ridge (see below), and the unconsolidated sediments that lie above the regional kurkar surface and below a relatively thin cover of the silt unit. These considerations guided us in determining the location of the coring and probing stations.

The purpose of the coring and probing was to obtain samples in order to determine the geotechnical properties of the potential fill material and the waste overburden, and to obtain information to calibrate the seismic record.

Altogether, 85 sampling stations were occupied. The kurkar ridge was cored in 19 stations, using a 6 m long diamond coring device. The unconsolidated sediments were cored in 44 stations using an 8 m long vibracore instrument. In addition, the unconsolidated sediments were probed in 32 stations with a 12 m long device (cone penetrometer) that produces a graphic log of the geotechnical properties of the section penetrated by it. The geotechnical and sedimentological tests of unconsolidated sediments and the kurkar sandstone recovered in the cores were carried out at the GSI (Almagor et al., 1998) and the Technion (Goretsky and Olshansky, 1998).

4.4. Potential offshore aggregate resources

For the purpose of the present discussion it is convenient to describe the shallow offshore sedimentary section as consisting of three principal lithologic-stratigraphic units. The lower unit consists of a consolidated sandstone, referred to locally as "kurkar". The kurkar unit is overlain by a sequence of unconsolidated sediments. The unconsolidated

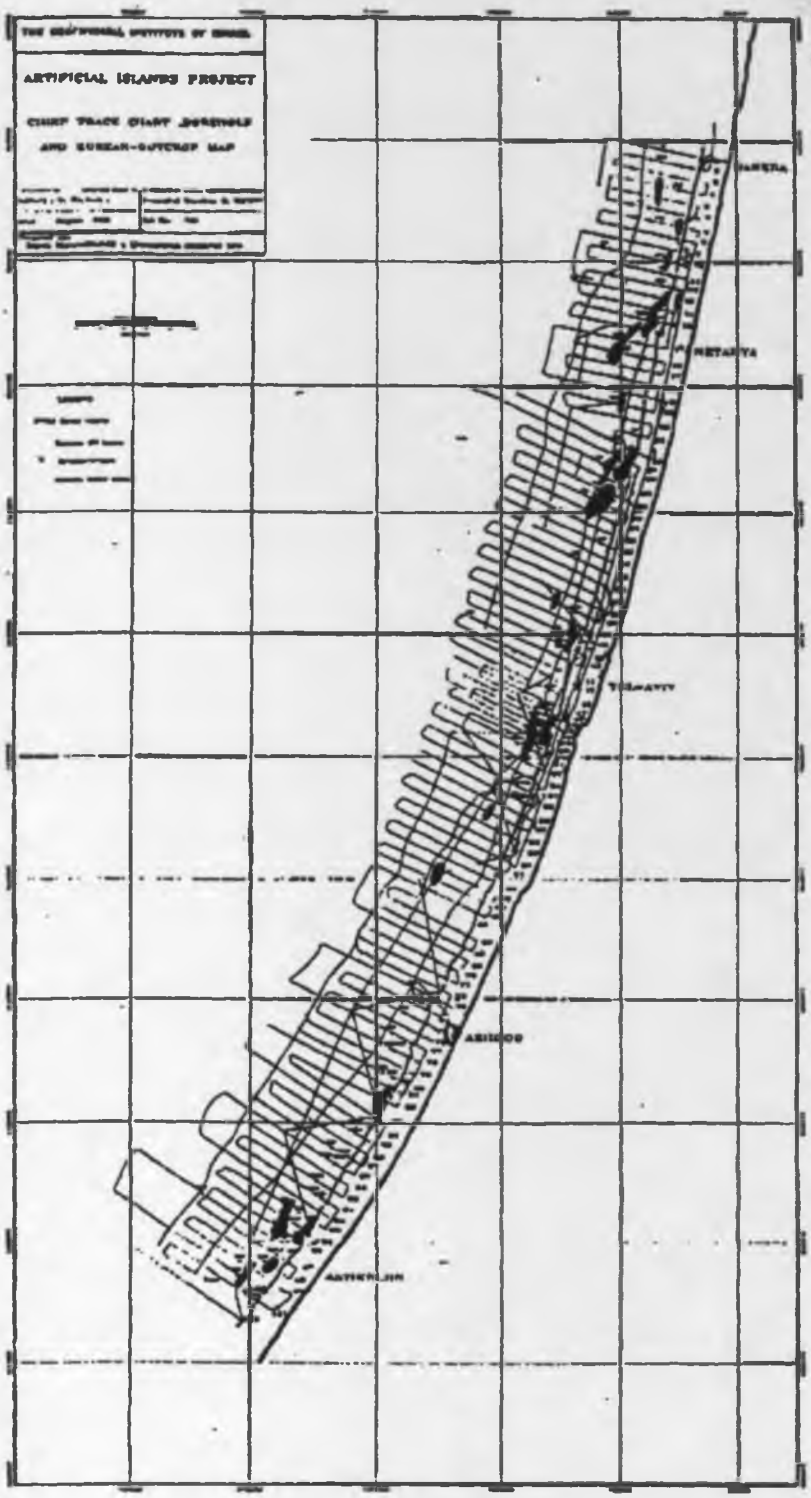

Figure 4.1. Track chart of the 1998 shallow seismic survey carried out by the artificial islands feasibility study project, and a map of the outcrops (black colored areas) of the easternmost submerged kurkar ridge.

sediments can be further divided into two subunits, a lower sandstone unit, and an upper unit consisting of dark gray silty clay.

4.4.1. The easternmost submerged kurkar ridge

The kurkar unit consists primarily of carbonate cemented quartz grains and subsidiary amounts of carbonate fossil fragments. This unit is several tens of meters thick. It underlies the entire continental shelf. It represents fossilized dunes that were formed during the late Pleistocene. The lithified dunes are disposed as several shore-parallel subdued ridges. The top of the kurkar unit is a regional unconformity surface that was formed during the large sea level drop at the end of the Pleistocene. The kurkar unit is overlain by a sequence of unconsolidated sediments of Holocene (14,000 years old and younger) age.

Of the offshore kurkar ridges, the easternmost ridge that is nearest to the present shoreline is the most prominent one. It consists of a series of chained hillocks that rise some 25 m above the surrounding regional kurkar surface. The kurkar ridge crops out above the sea bottom in many places. The relief of the outcrops above the surrounding sea floor is on the order of 10 to 15 m. The outcrops are commonly about 500 m wide and they are located at a water depth of 30-40 m, about 3-4 km from the shore. The location of the outcrops is shown in Figure 4.1. This kurkar outcrops map is based on the information obtained during the 1998 seismic survey.

The kurkar bedrock in the outcrops was sampled in 19 locations by 6 m long cores. The rock consists of well-sorted fine quartz sandstone (usually 0.074-0.300 mm) with abundant heavy minerals, skeletal debris and variable amounts of carbonate cement, ranging from hard to friable rock that yields 50-70% of loose sand with hardly any silt or clay. The upper surface of the kurkar outcrops is covered by a 0.5 m thick layer of dark gray, hard, biogenic crust. Its upper part is mostly algal, and its lower part is a thoroughly cemented calcrete, composed of indurated crust fragments with large inter-particle voids.

The geotechnical tests establish that the marine kurkar is suitable to serve as fill material. It occurs in water depths which are within the reach of the dredging equipment. After crushing the upper crust the material can be readily dredged at a cost of about 5 US$ per cubic meter.

The volume of kurkar in the outcrops within the area covered during the recent (1998) geophysical survey between Hadera and Ziqim is approximately 135 million cubic meters. Along some sections of the coast, the eastern kurkar ridge acts as a dam to the seaward transport of sands from the nearshore sand belt. As such it has an indirect role in protecting the stability of the coast. Furthermore, it supports a certain ecological niche of marine life. For these reasons the eastern escarpment of the ridge has to be preserved. This consideration reduces the reserves by about 30%. However, it should be stressed that the above estimate refers only to the portion of the kurkar which is exposed above the surrounding seabed. More material may be exploited beneath the sea bottom. Furthermore, based on earlier data, it is known that additional outcrops of the eastern kurkar ridge exit also north of the explored area, between Hadera and Haifa Bay, at water depths of about 30 m. Therefore, it can be concluded that the proven reserves of kurkar bedrock are sufficient for the construction of several 1 km^2 islands.

4.4.2. Offshore sub-bottom unconsolidated sands

The geophysical survey and the vibracores revealed that two sand units occur above the kurkar. The lower one, referred to as Sand I, overlies the kurkar and is found across the shelf, extending westward to a water depth of about 40 m. The other, Sand II, is found on top of Sand I in depths shallower than 30 m. The thickness of the two sand units ranges from zero to close to 30 m. The sand units are interbedded with beds of clay, silt and sandy silt. In most of the cores the sands were found to contain 35-50 percent grains finer than 0.075 mm.

As mentioned above, the sand unit is covered by a unit of silty clay. The thickness of the latter increases from zero at a water depth of approximately 20 m to more than 25 m at the western edge of the surveyed area. This unit has a rather uniform composition (an average composition of 29% silt, 67% clay and 4% sand finer than 0.5 mm) and it can be readily removed by dredging.

The volume of sand, buried beneath the silt, at water depths greater than 30 m, is estimated at 1.3 billion cubic meters. However, not all of these reserves can be exploited economically because of the thick overburden of silt material. Large reserves of sand, covered by a relatively thin overburden, are found opposite Hadera-Netanya, Ga'ash, Tel Aviv, Yafo, and Ashdod-Ziqim. In these areas, the volume of sand covered by an overburden of 3-6 m is about 335 million cubic meters, and an additional 265 million cubic meters are found beneath a cover 6-10 m.

However, as mentioned above, this sand contains 35-50% silt. As such, it is not suitable to serve as fill material for the construction of artificial islands, which according to the standards set by foundation engineers, has to consist of at least 90% clean sand. This notwithstanding, it should be noted that techniques are available to improve the sand quality by filtering out the fines during dredging operation and transportation of the material to the site of the island. This added treatment will increase the cost of the sand. The economic ramifications of sand filtering must be determined in order to determine the feasibility of using this resource.

5. SEISMIC HAZARD AND RISK ASSESSMENT

5.1. Introduction

One of the principal concerns in building artificial islands is their special vulnerability to seismic events. This vulnerability was manifested in 1995 when some artificial islands in Japan suffered significant damages during a strong earthquake. Therefore, an assessment of the seismic hazards in the proposed site is of utmost importance for evaluating the feasibility of the project. This chapter discusses the various aspects of this subject. The discussion is arranged as follows. The first section introduces some basic concepts and information about earthquakes which are pertinent to the subject matter. The next sections presents a review of the Japanese case history, and the lessons that can be drawn from it. I then proceed to review the methodology of seismic hazard and risk assessments, and the uncertainties that are inherent to these evaluations. The remainder of the chapter deals with the specific situation in Israel in general, and the proposed site in particular. It begins with a review of the general seismicity of the country, and continues with an assessment of the seismic vulnerability of the proposed site, and the preventive measures that should be undertaken to mitigate the potential dangers.

5.2. Basic concepts

Earthquake are the surface expression of seismic shock waves which are generated within the earth by the sudden slippage of large blocks in the earth's crust relative to one another along faults. Such sudden slippage happen when the amount of tectonic stress exceeds the mechanical friction between the blocks.

Presented below are definitions of concepts and technical terms which are pertinent to the present discussion.

The magnitude (M) of an earthquake is a quantitative measure of the amount of energy released by an earthquake at its focus (see below), interpreted from the maximum wave amplitude of the vibration recorded on the measuring instrument (seismograph), and corrected for the distance of the seismograph station from the epicenter. The scale of measurement is the Richter scale. Each unit on the Richter scale represents an amplitude that is 10 times greater than the next smaller unit (i.e. it is a base 10 logarithmic scale). For each successive unit on the scale the amount of energy released is about 30 times greater than in the lower unit. Using this scale, earthquakes are rated as insignificant (less than 4), minor (4-5), damaging (5-6), destructive (6-7), major (7-8) and great (over 8). Theoretically, there is no upper limit to the magnitude that an earthquake may assume.

The amount of energy released by a 6.5 earthquake is roughly equal to the energy released by the explosion of 10,000 tons of TNT (equivalent to the amounts of energy released by the Hiroshima atomic bomb). The magnitudes and amounts of energy releases by some of the most destructive earthquakes of this century were: San Francisco, 1906, M=8.2, 200,000 tons TNT; Mexico City, 1985, M=8.1, 350,000 tons TNT ; Armenia, 1988, M=6.9; California, Loma Prieta, 1989, M=7.1, 20,000 tons TNT; Iran, 1990, M=7.3; and Kobe, Japan, 1995, M=7.2 (Dolgoff, 1996, p.97). A table that summarizes the approximate relationships between magnitude-energy-epicentral acceleration, and between acceleration, intensity, and ground velocity is presented in Lomnitz and Singh (1976, p.12).

The earthquake's focus is the initial point of rupture within the earth from which seismic waves are generated.

The earthquake's epicenter is the location on the earth surface that is directly above the focus of the earthquake.

The intensity of an earthquake is a measure of the severity of the earthquake expressed in terms of destructiveness or inflicted damage. The intensity varies spatially as a function of the distance from the earthquake's epicenter and, in addition, it depends on the response of the topmost soil layers and the robustness of the manmade constructions at each site. The common scale in use is the 12-level Modified Mercalli intensity Scale (MMS) (see Amiran et al., 1993, App. 3). Significant damage to buildings begins to occur at level VIII.

The Peak Ground Acceleration (PGA) is a quantitative measure of the maximal ground shaking induced by an earthquake, usually separated into vertical and horizontal components, that can be expected at a given location, expressed relative to the acceleration of gravity (g).

Liquefaction is a process that can develop during an earthquake in a loose unconsolidated layer of porous granular material which is water-saturated (cf. Faccioli and Resendiz, 1976). This situation may be encountered in areas of very high water tables, such as wetlands, and it is particularly common in sea-side land reclamation projects, and in artificial islands which were built with granular fill materials. During an earthquake, the fluid pressure within the porous material rises instantaneously to a level that may exceeds the prevailing stable lithostatic pressure at the given depth. If this excess pressure cannot be released and dissipated at the same rate as it is building up, the particles become buoyant and the medium loses its shear strength and behaves like a quicksand or a fluid. The susceptibility of artificial fill materials to undergo liquefaction is the greatest seismic hazard in artificial islands. The damages caused by liquefaction to some artificial islands in Japan during the 1995 Kobe earthquake, and the remedies to mitigate this danger, are discussed in the next section.

5.3. The behavior of artificial islands during earthquakes – the Japanese experience

Japan provides a prime example of a situation in which population pressure on limited coastal land resources creates the need, justification and resolve to expand seaward. Marine land reclamation began in Tokyo Bay already in the 17th century. Today, Japan is the leading country in the world in reclaiming land from the sea by constructing artificial islands. By now, some 90 artificial islands, covering a total area of 560 km^2, have been constructed. Most of them were built along the densely populated eastern seaboard of

Japan, between Tokyo and Kobe (Murota et al, 1995). Needless to say, the extensive Japanese experience in all aspects of planning and building artificial islands is of great interest to planners elsewhere. However, two artificial islands in Osaka Bay, Port Island and Rokko Island, near the city of Kobe, are of particular interest to the present discussion because they are the only artificial island in the world which experienced a severe earthquake. The following paragraphs are devoted to a description of the behavior of these islands during the strong earthquake that occurred in Osaka Bay in 1995, and to the lessons that can be learned from this case.

The islands are situated in a protected bay, in shallow water depths of 10-15 m (Zimmels et al., 1993; 1996. Shelef and Zimmels, 1995. Zimmels and Shelef, 1996). Port Island covers an area of 4.36 km^2. The construction of the island itself required 80 million cubic meters of fill material. It took 5 years (1966-1971) and an expenditure of two billion US dollars. The fill material was obtained by leveling a mountain on land near the city of Kobe. The leveled area thus created was used to build the campus of the university of Kobe, a Hi-tech industrial park, and a sport and recreation center. The fill material used to construct the island consists of crushed igneous rocks and it contains less than 7% fines (silt and clay sized particles). Construction on the island was completed in 1980 at an additional cost of 2.5 billion US dollars.

Port Island is one of the largest harbors for container carrying ships in the world. The harbor covers an area of 1.5 km^2. The docking berths and the port facilities occupy about 55% of the reclaimed area. The share of other land uses is roughly as follows: 8% industry, commerce, offices, and municipal services; 22% residential, currently housing some 25,000 people; 5% parks; and 10% roads.

Since artificial islands are literally a virgin terrain their land use design present a big challenge and a unique opportunity for urban planners to devise and implement innovative optimal solutions. Craven (1995) describes some of the enlightened urban planning concepts which were implemented in Port Island. The transportation system in Port Island serves as an example for the many modern and innovative planning solutions which were implemented. Automotive traffic to the mainland is via a bridge. Vehicular traffic is separated from pedestrian traffic. An automated rapid transit system provides frequent, efficient, and convenient connection to the mainland and access to every part of the island.

Rokko Island was designed and built to stimulate Kobe's economy by providing additional port facilities, and to support urban development by providing additional land to relocate some public facilities out of the congested downtown area. The island's maximal dimensions are 3.4 km long and 2.0 km wide, and it covers an area 5.8 km^2. Its was built between 1972-1992. The water depth at the site is 14-15 m. Its construction required 120 million cubic meter of fill material. The construction costs were 4.5 billion US dollars for the island itself (sea walls and fill), and 5.5 billion US dollars for the buildings and facilities. The land use division is similar to that of Port Island: 28.8% ship mooring berths; 23.1% harbor facilities; 7.6% industry, commerce, offices, and municipal services; 22.6% residential, currently housing some 20,000 people; 6.0% parks; and 11.9% roads.

The construction of the islands was financed by the government of Japan. The essential urban infrastructures (roads, parks, public services) were developed by the city of Kobe. The area was then leased to the private sector who developed the commercial, industrial, and residential areas.

The Kobe earthquake (also referred to as the Hanshin, and the Hyogoken-Nambu earthquake) occurred on Jan. 17, 1995, at 05:46. The earthquake had a magnitude of 7.2 on the Richter scale and it lasted for 20 seconds. The epicenter was at the northern tip of Awaji Island, about 30 km west of Kobe, at a depth of 14 km. The tremor spread along a known 50 km long fault (the Nojima Fault, one of the faults in the Rokko fault swarm) that trends in a NE-SW direction and passes near Kobe. The last large earthquake on this fault occurred in 1916, and its magnitude was 6.1. In the 1995 earthquake most of the affected area experienced ground accelerations of 800 gals (i.e. 0.8 g; 1 gal = 1 cm/sec^2). Surface ruptures with vertical displacements of up to 0.5 m were observed in many places.

Kobe has 1.5 million inhabitants, and an additional 1.5 million people reside in its metropolitan area. The coastal zone between the Rokko mountains and Osaka Bay houses all the main transportation infrastructures of roads and railroads that lead from Tokyo and central and northern Honshu to the southern parts of Honshu and to Kyushu Island, which is the second largest of Japan's four main islands. Kobe has the second largest harbor in Japan (it ranks 6th in the world).

The earthquake's human toll in the city of Kobe was 5,472 deaths and 26,804 people injured. 83,536 houses were destroyed and 68,761 were severely damaged. 300,000 people remained homeless. 258 fires broke out within 24 hours after the earthquake due to failure of gas lines which devoured 671,253 m^2 of inhabited area and affected a total area of 1.3 million m^2. Due to the collapse of roads fire engines were not able to reach the area and extinguish the fires. The damage to roads was great and had the earthquake struck at a later time of the day when the traffic is very heavy there would have been many more casualties.

The direct damage to building and infrastructure was estimated at 100-140 billion US dollars. The relatively few deaths can be attributed to the high building safety standards that were progressively elevated following previous earthquakes in Japan, most notably following the 1923 7.9 strong Tokyo earthquake in which 140,000 people were killed and 560,000 houses were destroyed.

The earthquake effects in the islands were extensively documented and researched. The information presented below was obtained from the studies by Fukue and Kawakami (1996), Shibata et al. (1996), and Hatanaka et al. (1997).

The subsurface geological section in Osaka Bay consists of 15-20 m soft alluvial clay of Holocene age (accumulated in the course of the last 18,000 years). The unconfined compressive strength of the alluvial clay layer varies from almost zero to 100 kPa (kPa=1,000 Pascal) (i.e. the layer has a very low strength). Its liquid limit is 120% and its plastic limit is 30%. The alluvial clay overlies a 20 to 50 m thick layer of sand and silt below which are several hundred meters of hard Pleistocene clay with an unconfined compressive strength of 150-550 kPa. Solid granite bedrock is present at depth of 1,500 m.

The fill material in Port Island consists of a mixture of aggregates ranging in size from 0.2 to 8 mm (medium sand to gravel). The gravel content (particles larger than 2 mm) varied between 15-65%. Silt and clay constitute less than 10% of the fill. The material was primarily sandy soil from weathered granite excavated from Rokko Mountain west of Kobe (referred to as "Masa soil"). Sand drain installation were constructed in the central part of Port Island where apartment building were built. The fill material in Rokko Island consists of Masa soil and crushed volcanic tuff. The clay and silt contents in the tuff was 40- 55%.

Most of the structural damage in Port Island occurred in the peripheral sea walls along the perimeter of the island.. It caused collapse and destruction of wharves, piers, breakwaters, and the buildings that were situated on top of them. 179 of the 186 shipping berths were damaged. The average horizontal motion on the sea front structures was 2.7 m. The lateral displacements were confined to within 200 to 300 m of the perimeter. Around the perimeter the settling was 2 to 3 m. The damage was caused by the liquefaction of the fill material.

The damage to piers that were built of concrete caissons was up to 5 m lateral displacement, and up to 0.6 m vertical displacement. The failure of the caissons in the sea walls was not all due to liquefaction. Simultaneous horizontal and vertical accelerations ("shaking", "tremor") reduce the friction between the caissons and their substrate and initiate failure.

The buildings in both islands are typically 5 to 10 stories high residential apartments. There are also 20 stories tall office buildings and a 32 stories hotel in Port Island. All the tall buildings were built on piles that were founded in the sub bottom sand and gravel layer. Furthermore, the fill material in the island interiors was precompacted and sand drains were installed. As a result of these precautions the fill material did not liquefy. Throughout the interior of the island the settling was on the order of only 0.5 to 0.75 m, and most building did not suffer any damage.

The bridge that connects Port Island to the mainland was also damaged and four of its spans collapsed. The damage was due to liquefaction in the substrate in which the supporting columns were anchored.

Liquefaction is evident by the eruption of material and "sand boiling" that flows on the ground surface like a liquid. From air photos it was determined that close to half of Port

Island was covered by such flows. Liquefaction also occurred in the seabed clay that underlies the island which settled by 30-50 cm.

The damage in Rokko Island was much less because of the makeup of the fill material and the treatment that it underwent.. Here the fill material consisted of Masa soil and volcanic tuff. The fill was compacted with vibrators (vibro-compaction) and a fill drainage system was installed in compliance with the strict safety codes introduced in Japan in 1981. Due to these precautions the tuff, even though it contains a high percentage of silt and clay sized particles, did not liquefy and most of the structures and the high rise buildings remained intact. Also, no evidence of liquefaction in the underlying seabed was found. However, also here the railroad and highway bridges connecting the island to the mainland suffered great damages, including the complete collapse of several spans.

The main lessons that can be derived from the response of the Japanese artificial islands to a severe earthquake are as follows:

1. The main damage was caused because of the liquefaction of the fill material. The liquefaction of the fill material has several destructive effects:
(a) Due to the excessive pore pressure the tendency within the fill is for lateral dislocation and flow of material towards the least resistant boundary. In the case of artificial islands this is towards the perimeter of the island. This causes a substantial increase of pressure on retaining walls and may lead to their failure.
(b) Another free surface is the fill/air interface at the top of the fill. Flow towards the surface causes ground oscillations which opens joints and cracks in the ground.
(c) The foundation (fill) losses its bearing strength. If the foundations of structures are too shallow structures can topple or be twisted.
(d) Another possible response is ground settlement. The liquefied state is followed by settlement of particles, compaction, and release of fluids from the top in the form of mud eruptions from cracks, causing settlement within the fill and significant ground sinking at the surface.

The liquefaction propensity of the fill can be minimized or even completely prevented by the use of adequate fill materials and by a number of engineering measures designed to mitigate liquefaction (Noda, 1991; Yasuda et al., 1996; Stolbas, 1997). The fill material should not contain more than 10% fines (silt and clay sized particles). The fill should be thoroughly pre-loaded and compacted by using vibrators. In addition, an adequate drainage system should be installed in order to de-water the fill and enhance its ability to dissipate the hydrodynamic over pressures generated during seismic events.

2. The weakest and most vulnerable zone in the island is its perimeter which has one unsupported free face open to the sea. All the structural elements in this zone have to be duly reinforced. The concrete caissons and the other structural elements that form the core of the peripheral sea walls should be tied to each other firmly to prevent their collapse.

3. Because of the excessive vulnerability of the perimeter of the island it is advisable to leave a buffer zone without buildings along the perimeter.

4. High rise buildings should be anchored deep in the solid substrate below the fill.

5. The strictest safety codes employed in earthquake-prone countries like Japan and California should be adhered to.

5.4. Methodology of seismic hazard and risk assessments

The notion of seismic hazard pertains to the physical phenomena associated with earthquakes like ground shaking and liquefaction. Seismic risk is the likelihood of human and property loss that may result from the hazard. The objective of seismic hazard and risk assessments is to present an intelligent guess as to (a) the likelihood that a certain location may be affected by an earthquake of a certain magnitude within a prescribed time period, and (b) estimate the degree of damage (the intensity) that can be expected at that location.

Such assessments are most important for planning purposes in earthquake prone areas. Based on them it is possible to identify vulnerable places and prescribe countermeasures and engineering design parameters to mitigate or minimize anticipated damages. Among other things, such assessment are developed and used by the insurance industry to determine the costs of insurance programs against earthquake damages.

Assessing seismic risk entails the integration of seismic hazard and risk parameters. The main variables which determine seismic hazard are the location of active faults, the seismic activity (magnitudes, frequency, and recurrence interval of earthquakes) on these faults, the nature and material properties of the subsurface domain through which the seismic waves propagate, and the geothechnical properties of the topmost near-surface layer (the "site effect"). The engineering properties of the above ground structures determine their vulnerability to the seismic hazard, or their seismic risk. Seismicity is stochastic in time and space and, in addition, every one of the above mentioned variables cannot be accurately known. Therefore, the procedure involves unavoidable approximations and simplifications, and all assessments have a wide margin of uncertainty.

The assessment and mapping of seismic hazard is a complicated procedure (see discussion in Shapira, 1994a) that involves the following main steps:

The epicenters of earthquakes are located on, or in close proximity, to active faults. Active faults and their vicinities are referred to as seismogenic zones. One has to assume that the epicenters of future earthquakes can be located with equal likelihood anywhere in these seismogenic zones. The seismic waves are propagating from the earthquake's focus in all directions, and the shock vibrations are spread as body waves in the subsurface and as surface waves close to the ground surface. As a general rule, the vibrations will become weaker as one moves away from the epicenter (or focus). The attenuation depends on the seismic properties of the medium through which the seismic waves propagate. In a homogeneous medium, all other things being equal, the shock will progressively decrease with distance from the source. The attenuation function is determined empirically for each region by analyzing the relations between the epicenter location and the magnitudes of ground accelerations recorded at many locations away from the epicenter in many seismic events.

There are several statistical and Monte-Carlo simulation methods (which will not be presented here; see Shapira 1983a, 1983b, 1984) to arrive at a probabilistic statement about the maximum magnitude that is likely to occur in each seismogenic zone within a given time period. For example, based on long time seismic measurements, it is possible to state for a given fault that "it is 90% certain that within the next 50 years the strongest earthquake on the fault will not exceed a magnitude of 6.5". The magnitude-recurrence interval (frequency) characteristics are evaluated for all the active faults in the mapped area.

Thus far we have discussed three factors: the location of active faults, the seismicity of the faults, and the spatial attenuation function. Given these three, it is possible to produce a map that portrays, within a specified confidence level, the predicted peak ground acceleration at any point in the territory of interest for the maximal magnitudes that are likely to happen on the various faults within a specified time period. Such a map is referred to as a seismic hazard map, or a seismic alpha coefficient map. Such maps do not take into account the local site effects. In other words, it is assumed that the territory is everywhere underlain by solid rocks.

The estimated ground motion and the damage to structures at any given site (the intensity) are dependent on the peak ground acceleration (PGA), as expressed in the seismic hazard map, and on two additional variables, the response of the substrate at the site, and the vulnerability (engineering properties) of the structures.

The topmost near-ground layers, often referred to collectively as "soil", if less firm than the deeper subsurface bedrock, which they usually are, may amplify the seismic vibrations (cf. Faccioli and Resendiz, 1976). The amplified vibrations can be 2 to 7 times greater than the PGA at the top of the solid bedrock. Site effect may vary significantly from site to site over very short distances of tens of meters. Therefore, they have to be evaluated individually for each site.

An especially vulnerable situation arises when a site is underlain by a loose unconsolidated layer of porous granular material which is water-saturated. This situation may be encountered in areas of very high water tables, such as wetlands, and it is particularly common in sea-side land reclamation projects, and, of course, in artificial islands which were built with granular fill materials. As mentioned above, such substrates are susceptible to undergo liquefaction, loose their shear strength and behave like a quicksand or a fluid (cf. Faccioli and Resendiz, 1976). The susceptibility of artificial fill materials to undergo liquefaction is the greatest seismic threat to artificial islands. The damages caused by liquefaction to some artificial islands in Japan during the 1995 Kobe earthquake, and the remedies to mitigate this danger, were reviewed earlier in this chapter

Mexico City is built on a water-logged ancient lake deposit and the liquefaction of this substrate was the principal cause for the devastating results of the 8.1 strong earthquake that struck the city in 1985. Likewise, the damages incurred to buildings in the Marina District in San Francisco during the Loma Ptieta (in California) earthquake of 1989 was caused by the liquefaction of the fill material used in reclaiming this area from the sea (Plafker and Galloway, 1990; Stolbas, 1997).

The engineering vulnerability of above ground structures is relevant only where structures already exist, and it depends on the engineering characteristics of the structures in the area. Thus, the great physical destruction and the large numbers of human deaths and injuries caused by the recent earthquakes in Armenia (1988) and Iran (1991) were due mostly to poor construction of buildings.

The integration of the latter with the seismic hazard yields a seismic risk map. Such maps portrays the maximal seismic damage (intensity) that is likely ("10% chance") to occur at every site within a stated time period (usually 50 or 100 years).

5.5. Seismic hazard and seismic risk in Israel

5.5.1. General Seismicity of Israel

The seismicity of Israel is determined by its regional geotectonic setting. With reference to the major geotectonic elements in the region, Israel is situated on the Sinai (or Levant) subplate and is bordered by the stable Arabian craton on the east, the eastern Mediterranean Sea on the west, and the Alpine orogenic belt on the north. The main seismogenic zones of active faults in the region are the Dead Sea Transform (DST) fault, and the Zagros Mountains Fault and its extension into the Mediterranean south of Cyprus (Fig. 5.1).

The Dead Sea Transform, also known as the Syrian-African Fault, is a major tectonic feature of global scale. It extends for about 1200 km from the Turkish-Syrian border southward across the Beka'a Valley of Lebanon, the Jordan-Dead Sea-Arava Valleys in Israel, the Gulf of Elat (Aqaba), and into the Red Sea (Fig. 5.1). It is a plate boundary that separates the Arabian plate, on the east, from the Sinai subplate, on the west. In plate tectonic terms, it is a continental transform fault that connects the spreading center (a divergent plate boundary) of the Red Sea with the Afro-Eurasian plates collision zone (a convergent plate boundary), expressed on land by the Taurus Mountains of southern Turkey and the Zagros Mountains in Iran, and at sea by the subduction zone south of Cyprus. A 400 km long segment of this fault, from Elat in the south to Dan on the Lebanese border, passes through Israel.

The DST is a left lateral strike slip fault with a displacement of 105 km. Along it the Arabian plate is moving northward relative to the Levant subplate at a rate of circa 0.5

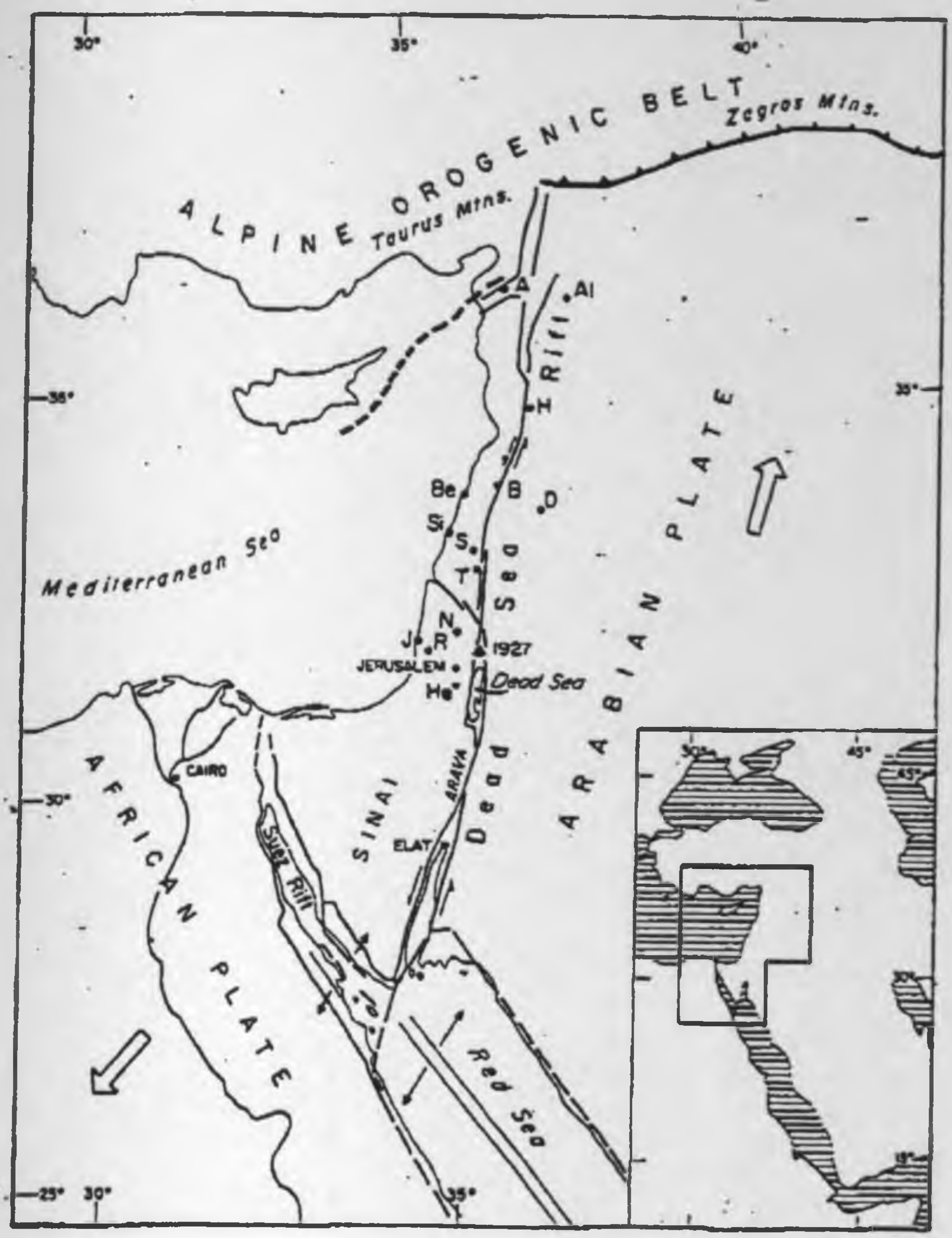

Figure 5.1. Regional plate tectonic setting of the Sinai subplate and the Dead Sea Transform. Main cities: A – Antiochia; Al – Aleppo; H – Hama; B – Baalbek; Be – Beirut; Si – Sidon; S – Safed; T – Tiberias; N – Nablus; J – Jaffa; R – Ramla; H - Hebron (from Garfunkel et al., 1981, fig. 1).

mm per year as the Red Sea is opening and a new ocean is being formed. A branch of the DST, the Carmel-Fari'a fault, crosses central Israel in a northwest direction from the Jordan Valley to the Mediterranean. This active fault zone has one of the longest documented record of destructive earthquakes in the history of mankind (see below). The subduction zone south of Cyprus is also an active seismic belt. Submarine earthquakes along the latter have initiated tsunamis (seismic sea-waves) which caused some destruction in coastal towns along the southeastern Mediterranean, including Israel (see below).

The seismic activity in the region is shown in Figure 5.2 which depicts the epicenters and magnitudes of earthquakes (with $M \geq 3$) recorded between 1900-1996 (Shapira, 1997). The map is based on data recorded by the 36 stations of the Israel Seismic Network (for the period 1981-1996), and on data assembled from other seismic stations in the region (Arieh et al., 1985).

Altogether, the area has a fairly high seismic activity, luckily mostly of weak events. It can be seen that most of the epicenters, and especially the larger earthquakes, are concentrated along the three seismogenic zones described above. However, there is also weak seismic activity which is scattered throughout the map which is not associated with recognized active faults.

A particularly large concentration of seismic events occurred along the Gulf of Elat. The largest earthquake recorded in the mapped area, the Nueiba earthquake of Nov. 22, 1995, which had a magnitude of 7.1, occurred in this segment of the DST. This earthquake caused minor damages in the city of Elat and was felt mildly throughout Israel. Another relatively large earthquake with a magnitude of 5.9 occurred in the Gulf of Elat in 1993. Another cluster of earthquakes is concentrated along the Dead Sea. The strongest earthquake in this part of the DST occurred in 1927. Its epicenter was near Jerico and it had a magnitude of 6.2. The strongest earthquake recorded on the Carmel-Fari'a fault occurred in 1985 with a magnitude of 5.3.

The cluster of events along the subduction zone south of Cyprus is 300 km away from the Israeli coast. Earthquakes in this seismogenic zone, including the strongest recorded one, the 7.8 earthquake which occurred in Papos, Cyprus in 1953, have caused only slight tremors in Israel. However, earthquakes in the Mediterranean may initiate tsunamis, which pose a significant threat to the coast in general, and to artificial islands in particular. This matter is discussed further below.

The instrumentally measured record can in the case of Israel be augmented by additional information from historical chronicles and archaeological records of destruction in ancient settlements that go back in time some 2,000 years (see for example Nur and Ron, 1996). Data on historical earthquakes in Israel and its vicinity are presented in the catalogues published by Amiran (1951; 1952), Amiran et al.(1994), Ben-Menahem et al. (1976), and Ben-Menahem (1979; 1991). The most recent updated catalogue by Amiran et al.(1994) lists 65 events from 92 BC to 1800, and 27 events during the 19th century.

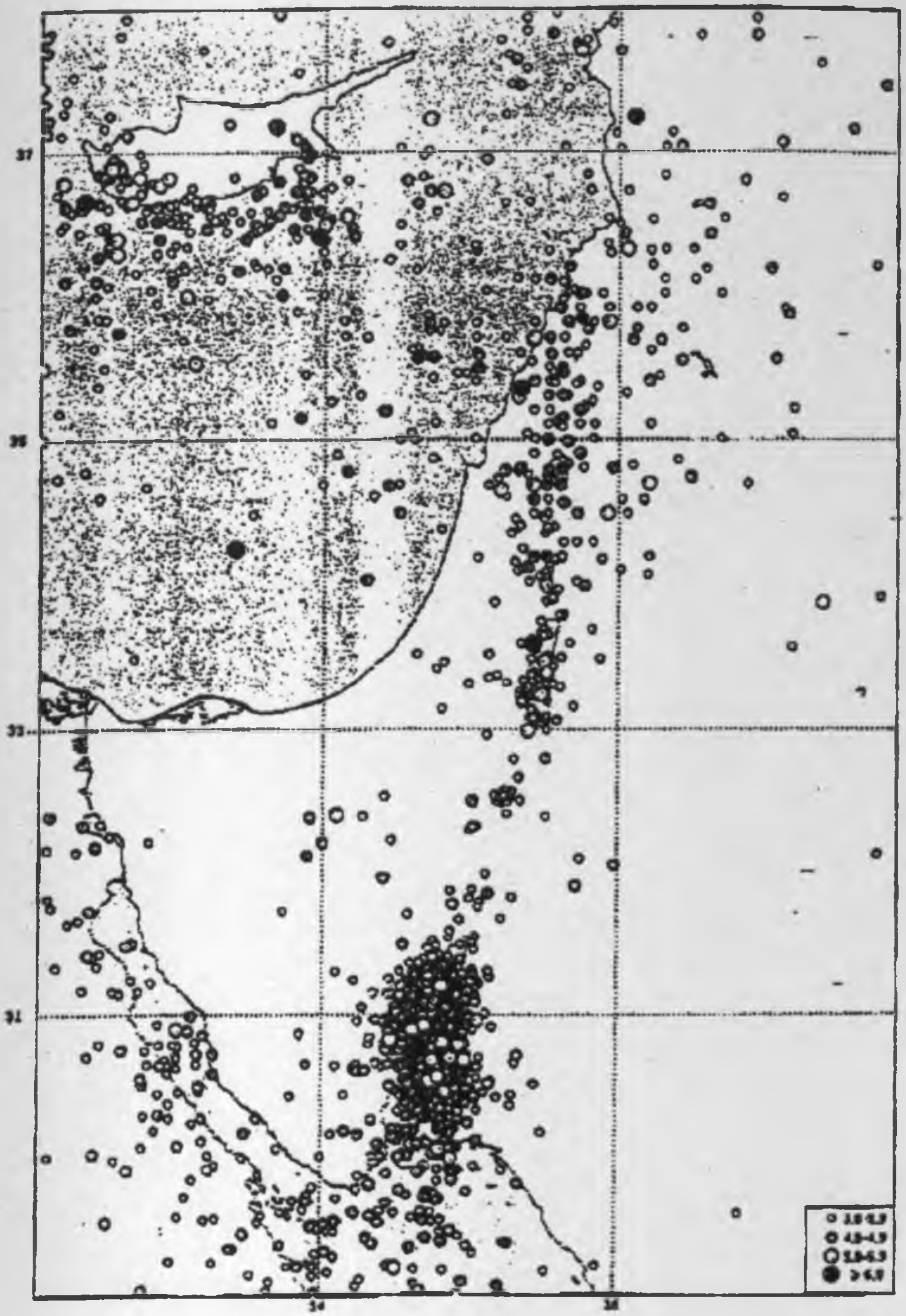

Figure 5.2. Epicenter map of earthquakes with a Richter magnitude greater than 3.0 that occurred in Israel and surrounding areas between 1900 and 1996 (Shapira, 1997).

The interpretation of the historical records and their transformation into useful seismologic information in terms of epicenter location and source magnitude present many difficulties (cf. Ambraseys and White, 1997). Based on the severity and geographical extent of the damage as described in ancient chronicles it is possible to estimate the intensities in these locations. Next, using the rough correlation between MMS intensities and Richter magnitudes tailored specifically for historical earthquakes (Rapp, 1986), it is possible to estimate the location of the epicenter and the magnitude of the event (Ambraseys 1971, Rapp, 1986).

The historical records thus provide valuable information on the long term seismicity of the country. Specifically, one can estimate from the historic record the maximum magnitudes which were experienced in the past, the recurrence period of destructive events, and the location of epicenters and vulnerable areas.

Arieh and Feldman (1985) analyzed the historical data and identified 14 strong earthquakes of the "damaging" class which had magnitudes greater than 5.5. The epicenters of all of them were along the DST. The dates and the range of the estimated magnitudes (in parentheses) of these earthquakes are: 746 (6.7-7.2); 853 (5.8-6.2); 1033 (6.3-6.7); 1060 (5.7-6.1); 1068 (6.0-7.4); 1160 (5.6-5.9); 1202 (7.2-7.4); 1293 (5.9-6.5); 1458 (5.6-6.1); 1546 (6.7-7.2); 1759 (6.5-7.0); 1834 (5.6-6.0); 1837 (6.5-7.0); 1903 (5.6-5.7).

Apparently, prior to the 1995 7.1 Nueiba earthquake, the largest earthquake to hit the area occurred on May 20, 1202 in the northern Jordan River Valley. Its magnitude was on the order of 7.2-7.4. This earthquake left a remarkable physical evidence in the area. Archaeological excavations in the Crusader castle of Vadum Jacob in the northern Jordan River Valley exposed E-W trending walls that were displaced synistrally by up to 2.1 m (Ellenbaum et al., 1998). This displacement was most probably caused by a left-lateral strike slip fault which ruptured the surface during this earthquake. Among other things, this important find reconfirms that the DST is indeed a left-lateral strike slip fault.

Based on an analysis all the measured and historical data, Arieh (1994) presented a comprehensive evaluation and synthesis of the seismicity of Israel and adjacent areas. He concluded that all the significant earthquakes can be attributed to displacements on the DST and the Carmel-Fari'a fault. He presents estimates for the return periods of potentially damaging earthquakes (magnitudes ≥ 5.5). The return period for M=5.5 earthquakes is 25 years, and it increases exponentially as the magnitude rises. His analysis indicates that the magnitude of the maximal possible earthquake is 7.7 ± 0.5, with a return period of 10,000 years.

5.5.2. Seismic hazard and seismic risk maps of Israel

The "official" seismic hazard map of the country, prepared by Israel's Institute of Petroleum Research and Geophysics to serve as the reference for the implementation of earthquake safety measures in compliance with the Israeli building standards code 413, is shown in Figure 5.3 (Shapira, 1994). The map is based on an analysis of observed seismic intensities (Feldman and Shapira, 1994) and the seismicity parameters of recognized seismogenic zones as evaluated by Shapira and Shamir (1994). The seismic hazard is defined as the potential horizontal peak ground accelerations (seismic alpha coefficients) on the solid bedrock, which have a 90% probability of not being exceeded within a period of 50 years (i.e. the maximal horizontal PGA that has a 10% likelihood within a 50 years period). It should be emphasized that the evaluation assumes a solid bedrock throughout, and that the potential modifications (amplification or deamplification) due to site effects are not represented. The level of seismic hazard decreases gradually westwards and southwestwards as one moves further away from the north-south oriented seismogenic DST fault and the NW-SE oriented Carmel-Fari'a Fault. The maximal potential PGAs in the northern Jordan River Valley are 0.25-0.3 g, and the values decrease gradually across the map to 0.05 in the south-western part of the map.

Maps that portray the spatial distribution of the estimated potential seismic risks throughout the country have been prepared by Wachs (1993) and by Shapira and Feldman (1994). As described above, seismic risk pertains to potential damage expressed in terms of the 12-level Modified Mercalli intensity Scale. In order to assess seismic risks consideration has to be given to the amplification of the ground accelerations that can occur due to the presence of different unconsolidated substrates in the near surface soil layers. For this purpose Wachs (1993) reclassified the geological units in the 1:250,000 scale geological map of the country that are covering the surface into eight geotechnical classes, in accordance with their different propensities to amplify the ground accelerations during seismic events. The map of the distribution of these units provides a map of the "infrastructure conditions" of the country (Wachs, 1993, figure 2). This map was then integrated with the alpha coefficient map to produce the seismic risk (intensity) map (Wachs, 1993, figure 3). Shapira and Feldman (1994, figure 3) followed essentially a similar procedure but employed a different convolution function to integrate the infrastructure conditions and the alpha coefficient maps.

5.6. Seismic hazard to artificial islands offshore Tel Aviv

According to the seismic hazard map (Fig. 5.3), the site of the proposed islands offshore Tel Aviv may experience PGAs of 0.05-0.075 g. Thus, the seismic hazard is extremely low. Likewise, on the basis of the seismic risk maps of Wachs (1993) and Shapira and Feldman (1994; Fig. X.x), the maximal estimated intensities in the proposed site are VI-VII, which are also quite mild. These assessment are in agreement with the actual intensities which were observed in this area during this century, which did not exceed MMS VII (for details see Amiran et al., 1994).

Most of the cataloged historical earthquakes, including most of the stronger ones, were not felt in the coastal towns in central and southern Israel. The 363, 672, 1114 and 1837 earthquakes were only felt in this area, without inflicting any damage. However, three earthquakes did cause severe damages in this area: the 130 earthquake in Ceasarea, the 1033/34 earthquake in Ashqelon and Gaza, and the 1546 earthquake in Jaffa. Most likely,

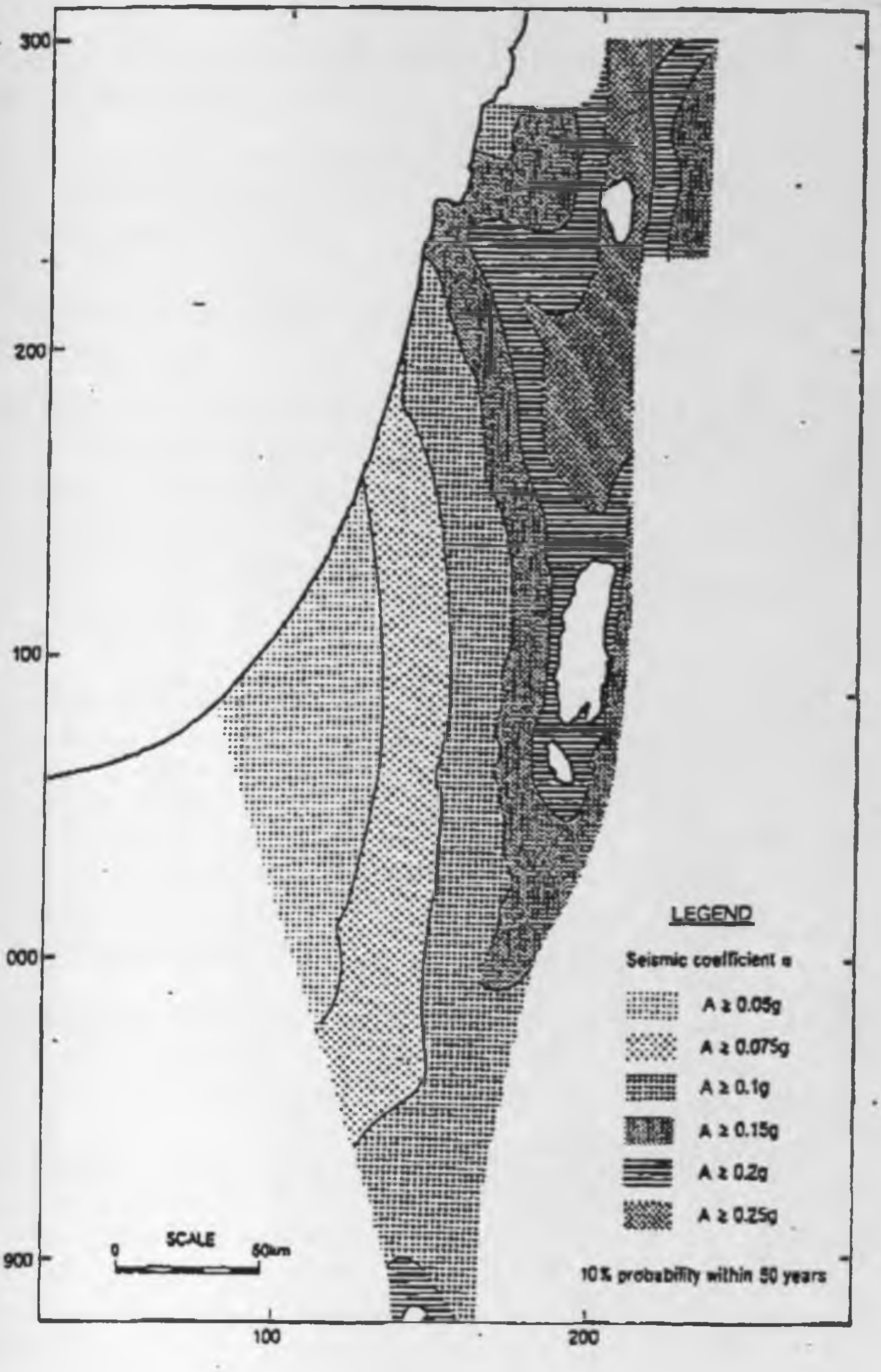

Figure 5.3. Seismic hazard (alpha coefficient) map of Israel. The isopleth lines indicate peak ground acceleration in solid bedrock, in g (gravity acceleration) units, which have a 90% probability of not being acceded within a period of 50 years (Shapira, 1994).

the damages were due to the vulnerability of the buildings and also in these cases the intensities were smaller than VII.

The seismic hazards at the site proposed for the artificial islands were investigated by Frydman and Talesnick (1999). The potential earthquake induced problems can be divided into four categories:

(1) *Problems associated with the seismic behavior of the sedimentary section under the island's site*

There is no direct information on the exact nature and geotechnical properties of the rock sequence below the proposed site. The closest deep (circa 100 m deep) boreholes that were drilled into the seabed at comparable water depths of 10 to 20 m are located offshore Hadera, some 50 km north of the site. These control points are too far away to facilitate a reliable forecast. Therefore, if the building of the islands will be seriously considered, deep boreholes will have to be drilled at the site in order to acquire the needed information.

On the other hand, the information available from geophysical surveys and shallow borings is quite adequate to infer the startigraphy and lithology of the topmost 20 to 30 m of the seabed at the site. All along the coast south of Haifa Bay, from the shoreline to a water depths of about 30 m, the upper part of the underwater sedimentary section consists, from top to bottom, of three layer: a 5 m thick layer of unconsolidated quartz sands, a 4 to 7 m thick layer of normally consolidated clay, and a layer of dense calcareous sandstone (kurkar), which is in places interbedded with thin intervals of loose sands, which is at least some tens of meters thick.

Each of the three layers can be expected to respond differently to seismic events. The kurkar layer at the bottom of the section can be regarded as solid bedrock and it does not present any immanent dangers to the stability of the island.

The normally consolidated clay layer can be expected to undergo additional compaction under the additional load that will be created by the artificial island. This will result in a slow continuous settlement which will affect the islands surface as well. Furthermore, the compaction process may extend over a long period of time. During this period the clay layer will effectively be in an under-consolidated state. Clays in such a state may suffer shear failure during an earthquake..

The sand layer at the top has a high liquefaction potential because of its loose constitution and high water saturation.

(2) *Problems associated with the seismic behavior of the fill material*

As mentioned above, the island will be constructed of granular fill material which has a strong propensity to liquefy. Remedial measures will have to be taken to reduce the risk of liquefaction. These are described below.

(3) *Potential acceleration amplification problems*

As far the combined behavior of the natural substrate and the fill material is concerned, Frydman and Talesnick have simulated the possible response. Their model of the infrastructure at the island's site consisted of consolidated bedrock at 65 m overlain by a 50 m thick layer of dense sand, a 10 m thick layer of normally consolidated clay, and a 5 m thick layer of loose sand. The island fill was positioned on top of this section, consisting of a 40 m thick heap of granular material, the topmost 10 m of which extended above the water surface. "Input earthquakes" were introduced with intensities of 5.2 to 7.2 and focal distances of 20 to 120 km. The modeling results show that under the specified conditions a deamplification of the accelerations are predicted, with peak accelerations decreasing from 0.2 g in the bedrock to 0.07-0.09 g at the surface. The maximum surface horizontal seismic displacement was predicted to be on the order of only 1 cm.

(4) *Earthquake induced tsunami hazard*

In addition to the seismic geotechnical problems related to the behavior of the seabed profile and the fill material, consideration must also be given to the effects of tsunamis that may develop during seismic events. Information on historical incidences of tsunami waves in the region were reviewed by Shalem (1956), Ambraseys (1962), and Amiran et al. (1994, App. 5). These sources list 18 possible tsunamis events which occurred in the last 2,000 years. The historical records do not describe the height of the waves which hit the shore during these events. Most of the reports describe a temporary recession of sea rather than an inundation of the coast. The tsunami that was associated with the strong 1202 earthquake caused serious damage in 'Akko.

Streim and Miloh (1976) analyzed the sea-recession events reported in 23 BC, 115 CE, 551, 1033, 1068, 1546, and 1759. Some are correlated with known earthquakes which occurred along the Dead Sea Transform. They conclude that the earthquakes triggered submarine slumping in the Mediterranean which in turn caused the development of tsunamis. According to their analysis the tsunamis which are initiated in this fashion may develop waves which can be up to 10 m high. Thus, the design of the island should take this possibility into account.

Based on the lessons learned from the behavior of the artificial islands in Osaka Bay during the Kobe earthquake, the following special preventive measures can be prescribed to mitigate the potential seismic hazards to the artificial islands offshore Tel Aviv:

1. The compaction process of the normally consolidated clay layer can be accelerated substantially by installing "sand drains" that penetrate the clay horizon. With this device the compaction may be completed during the building of the island.

2. The layer of loose sand and the fill material should be pretreated to prevent their liquefaction. Noda (1991) presents a summary of the most effective techniques in use to mitigate this problem. The principal objectives are to compact and de-water the granular

medium. The most common compaction methods are the "sand compaction pile" and the "vibro compaction" procedures. To de-water the granular medium and improve its drainage, an adequate number of "sand drains" have to be installed. A casing is set into the ground to the desired depth. Sand of high permeability is pored into the casing, and the casing is withdrawn, thereby introducing a permeable conduit into the fill.

In addition, the design and safety recommendations which arose from the Japanese case studies, some of which were outlined above, should be adopted and implemented

6. SUMMARY AND CONCLUSIONS

Israel is developing into one of the most densely populated countries in the western world. The high population density and shortage of land situation are most acute along the Mediterranean coastal plain where about 70% of the country's population is concentrated in urban communities. The city of Tel Aviv is located in the center of this belt. It is the principal commercial, business and cultural center of the country. The rapid population growth in Tel Aviv exerts an ever-increasing demand on land, which is already in short supply. The general rise in the standard of living, along with the associated rise in the demand for leisure and recreation facilities, and the rise in tourism, would increased the demand for seaside land of which there are no tracts left at all.

The city of Tel Aviv suffers from another acute problem due to its municipal airport which is located in the middle of a residential area. The airport traffic is an environmental nuisance and a safety threat to its immediate neighborhood. Furthermore, the airfield occupies most valuable tracts of land, and the air traffic space which it occupies prevents the construction of high rise buildings for miles around it. The airfield obstructs the development of a much needed main traffic artery and, altogether, disrupts the functional integrity of the urban fabric.

Conclusion: In view of the already extremely high land prices in Tel Aviv and its vicinity, it appears that artificial islands could become an economic viable alternative to land onshore, and a solution to the shortage of seaside land in particular. The only sensible alternative location for the municipal airport, which should preferably be close to the town's center, is an offshore island. An airfield at sea would alleviate the acute problems of safety, noise, and building restrictions. **

In view of this realization, the government of Israel and the government of The Netherlands (the latter because of its interest to promote the international business of Dutch marine engineering firms), sponsored a project whose objectives were to investigate several crucial questions that determine the feasibility of constructing residential islands and an airport island offshore metropolitan Tel Aviv.

Based in part on the findings of this project, the present report addressed the aspects which may determine the viability of the enterprise that are related to the local geological and sedimentological situation. Its specific objectives were to answer three cardinal questions: Can the islands be built without inflicting an irreparable damage to the coast? Are there sufficient local reserves of suitable marine fill material? Can the islands sustain the seismic hazard?

(1) <u>The sedimentological conditions and the overall sand balance in Israel's littoral zone</u>

Israel's littoral zone receives a constant influx of sands from the Nile delta by longshore currents. Yet instead of coastal accretion, the Israeli coast is experiencing long term erosion, manifested by the retreat of the shoreline and the backshore cliffs, and by the

** See note on island types, following page 2.

recent uncovering of archaeological remains in the foreshore due to removal of their protective sands.

The negative sand balance is due primarily to human action. The mining of sand (which was outlawed in 1964) and the coastal structures (harbor and detached breakwaters, groins) that block the longshore sand transport have withdrawn from the coastal system some 20 million cubic meters of sand. The natural inflow of sands at Gaza amounts to about 400,000 cubic meters per year. Thus, the manmade deficit is equivalent to 50 years of natural supply. The deficit is also caused in part by natural processes that transport sand out of the coastal system to deeper water and by winds that transport sands from the beaches to inland dunes.

Conclusions: (a) The Israeli coast suffers from a negative sand balance. The coastal system is very vulnerable to manmade obstacles that block the nourishment of beaches by the longshore sand transport. Artificial islands pose such an environmental threat.
(b) Mining of sands from the nearshore zone down to a water depth of 30 m will be replenished by the withdrawal of an equivalent volume of sand from the coastal system, resulting in coastal erosion. Therefore, the mining of sands from the nearshore sand belt should be disallowed.

(2) <u>Assessment of the adverse effects that an island may have on the coastal environment, and the measures that should be taken to rectify these impacts</u>

The long-term effects that artificial islands may have on the coast morphology were evaluated by numerical simulation. programs that use the sea bottom topography, schematized characteristic data on wind, tide, wave, and current climate, and sedimentological data about the longshore sediment transport to explore the impacts generated by different alternative configurations of island's shapes, sizes, and distance from shore.

The models provide quantitative estimates on the development of a tombolo between the island and the coast, and the extent of coastal erosion north of the island. These impacts are evaluated for selected time increments (e.g. 10, 50, and 100 years) after the construction of the island. Each simulation run addresses a specific island layout. The practice is to change the value of a certain design parameter, like the distance from shore, and observe the impact of this change. In this fashion it is possible to investigate the impact of individual design and location parameters and devise an optimal solution.

Conclusion: A 2,000 dunam drop-shaped island located 1,000 m from shore is the best solution for a residential island. A distance of 2,500 m is the best solution for the airport island. The islands will cause the development of tombolos on their lie side and erosion to the coast that lie to the north of them. To prevent these negative impacts, it will be necessary in the case of the residential island to dredge each year a volume of 100,000 m^3 to prevent the growth of a tombolo, and supply 300,000 m^3 of sands to the beaches that lie to the north of the island. The remedial maintenance operations that are required to prevent the negative impacts of the airport island are about twice as extensive and expensive as the ones needed for the residential island.

(3) Assessment of the availability of suitable marine aggregate resources for island fill material

The residential and the airport islands will require for their construction some 70 and 90 million cubic meters of fill material, respectively. The availability and timely supply of sufficient amounts of adequate fill material thus become a categorical condition for the ability to construct the islands in the first place. Likewise, the cost of the fill material at the island's site is one of the principal determinants of the economic feasibility and cost effectiveness of the endeavor.

Since there are no sufficient onshore resources of fill material in Israel, and because the costs of importing material from Egypt or Jordan will probably be prohibitively high, the ability to construct the islands may hinge entirely on the availability of sufficient amounts of suitable fill material in the offshore.

The suitability constraints prescribe that (a) the material has to possess adequate geotechnical properties (aggregates with less than 10% of fine silt and clay sized particles); (b) the resource has to be found at a depth of less than 60 m in order to be accessible by existing bottom dredging equipment; (c) the extraction costs should be acceptable; and (d) the exploitation of the resource should not cause adverse environmental effects.

The joint Israeli-Dutch artificial islands feasibility study project carried out a seismic survey and a seabed coring and probing program design to locate potential aggregate reserves on the sea bottom, or at a very shallow depth below the sea bottom, determine their suitability as fill material, and define the spatial distribution, thickness and volume of the reserves, and the thickness of waste overburden that has to be removed in order to exploit them.

The seismic survey covered the nearshore zone of the southern part of Israel's continental shelf, between Hadera and Ziqim, in water depths between 25 and 70 m. The area was surveyed by 118 shore-perpendicular seismic profiles spaced one kilometer apart. The seismic equipment consisted of a CHIRP sub-bottom profiler that can penetrate to a depth of about 35 m, with a vertical resolution of 10 cm.

Based on the analysis of the seismic records and on a compilation of data from previous studies of the continental shelf, two potential aggregate resources were targeted for coring and probing, outcrops of the easternmost submerged kurkar ridge, located in water depths of 30-40 m, and the unconsolidated sediments that lie above the regional kurkar surface and below a relatively thin cover of the silt unit in water depths of 30-50 m. Altogether, 85 sampling stations were occupied. The kurkar ridge was cored in 19 stations, using a 6 m long diamond coring device. The unconsolidated sediments were cored in 44 stations using an 8 m long vibracore instrument. In addition, the unconsolidated sediments were probed in 32 stations with a 12 m long device (cone penetrometer) that produces a graphic log of the geotechnical properties of the penetrated section.

The marine kurkar consists of well-sorted fine quartz sandstone, with variable amounts of carbonate cement, ranging from hard to friable rock that yields 50-70% of loose sand with hardly any silt or clay. The geotechnical tests establish that the marine kurkar is suitable to serve as fill material. It occurs in water depths which are within the reach of the dredging equipment. The material can be readily dredged at a cost of about 5 US$ per cubic meter.

The volume of kurkar in the outcrops within the area covered during the recent (1998) geophysical survey between Hadera and Ziqim is approximately 135 million cubic meters, about 70% of which can be mined without causing adverse effects. More material can be exploited beneath the sea floor, and additional reserves exist north of the explored area.

The geophysical survey and the vibracores revealed that two sand units occur above the kurkar. The lower one, referred to as Sand I, overlies the kurkar and is found across the shelf, extending westward to a water depth of about 40 m. The other, Sand II, is found on top of Sand I only in depths shallower than 30 m. The thickness of the two sand units ranges from zero to close to 30 m.

The sand units are covered by a unit of silty clay. The thickness of the latter increases from zero at a water depth of approximately 20 m to more than 25 m at the western edge of the surveyed area. This unit has a rather uniform composition and it can be readily removed by dredging. Large reserves of sand, covered by a relatively thin overburden, are found opposite Hadera-Netanya, Ga'ash, Tel Aviv, Yafo, and Ashdod-Ziqim. In these areas, the volume of sand covered by an overburden of 3-6 m is about 335 million cubic meters, and an additional 265 million cubic meters are found beneath a cover 6-10 m. These sands can be recovered at a cost of about 5 US$ per cubic meter.

The sand units are interbedded with beds of clay, silt and sandy silt. In most of the cores the sands were found to contain 35-50% grains finer than 0.075 mm. As such, these sands are not suitable to serve as fill material. However, it should be noted that techniques are available to improve the sand quality by filtering out the fines during the dredging operation and the transportation of the material to the site of the island. Therefore, in order to determine the adequacy of this resource, it remains to be determined whether the required level of purity can be achieved at acceptable costs.

Conclusions: (a) The marine kurkar is suitable to serve as fill material, and its proven reserves are sufficient for the construction of the residential and airport islands. (b) In the study area there are sufficient reserves (some 600 million cubic meters) of unconsolidated sands that can be extracted at acceptable costs. However, these sands contain too much fine material. Therefore, their suitability depends on whether they can be filtered to the required 90% purity at acceptable costs.

(4) Seismic hazard and risk assessment

One of the principal concerns in building artificial islands is their extreme vulnerability to seismic events. The vulnerability is due to the propensity of the fill material to undergo liquefaction under seismic tremor. Liquefaction is a process that can develop during an earthquake in a medium consisting of a water-saturated unconsolidated porous granular material wherein the medium loses its shear strength and behaves like a quicksand or a fluid. This peril was manifested in 1995 when two artificial islands in Osaka Bay, Japan suffered significant damages during a strong (7.2) earthquake. Therefore, an assessment of the seismic hazards in the area designated for the construction of the island is of utmost importance for evaluating the feasibility of the project, and for formulating the proper remedial measures to minimize the risk.

The assessments of seismic hazard and risk in Israel are based on an extensive data base of past seismic events and on very detailed information about the geological substrate, the distribution of active faults, and the overall seismicity of the region.

The data base on past seismic events includes 100 years of instrumental measurements and additional information from historical chronicles and archaeological records of destruction in ancient settlements that go back in time some 2,000 years. The historical records provide valuable information on the maximum magnitudes which were experienced in the past, the recurrence period of destructive events, and the location of epicenters and vulnerable areas. The historical data indicates that in the past 2,000 years the country experienced 14 strong earthquakes of the "damaging" classes which had magnitudes in the range of 5.5 – 7.4. Altogether, the area has a fairly high seismic activity of mostly weak (below 5.5) events. Most of the epicenters are distributed along the Dead Sea Transform (DST) fault, and their shocks were only mildly felt in the coastal towns in central and southern Israel.

According to the seismic hazard and risk maps, the site of the islands may experience peak ground accelerations of 0.075 g, and a maximal intensity of VII. These assessments are born out by the actual intensities which were observed in this area during this century, which did not exceed the level VII.

Earthquakes with epicenters on the DST and in the Mediterranean can generate tsunami waves that would constitute a hazard to the islands. The historical record indicates the incidence of 18 past tsunamis, only one of which caused serious damage in the coast. However, numerical modeling studies indicate that large scale earthquake-induced slumping in the continental shelf may give rise to tsunami waves that can be up to 10 m high. The design of the island should take this potential hazard into account.

There is no direct information on the exact nature and geotechnical properties of the rock sequence below the proposed site. Therefore, if the building of the islands will be seriously considered, deep boreholes will have to be drilled at the site in order to acquire the needed information.

The specific local seismic hazards that are due to the local site effects at the proposed site, which can be identified at the present stage, are the liquefaction potential of the sandy seabed and the fill material, and the compaction and settlement of the clay layer beneath the sand under the island's load.

Based on the lessons learned from the behavior of the artificial islands in Osaka Bay during the Kobe earthquake, the principal preventive measures to mitigate the potential seismic hazards to the artificial islands offshore Tel Aviv are the use of suitable fill material, installation of sand drains in the clay and sand layers and the fill material, compaction of the fill material, and reinforcement of the seawalls that enclose the fill. In addition, the strictest engineering safety standards employed in earthquake-prone countries like Japan and California should be adhered to.

Conclusions: (a) The seismic hazard at the proposed site is very low. (b) Additional investigations are requited to determine the specific local site effects. (c) The design of the islands should take into account possible 10 m high tsunami waves.(d) In spite of the optimistic outlook, all the known precautionary measures and the strictest safety standards should be implemented in the construction of the islands and their above surface structures.

In summary, it appears that the answers to the three questions posed at the outset of this study are in the affirmative: (a) The adverse environmental impacts of the islands can be rectified. (b) There are sufficient local suitable marine aggregates to build the islands. (c) The seismic hazard is small, and the risks can be minimized by implementing proper precautionary engineering measures. Therefore, as far as the geological aspects of the project are concerned, it can be considered to be a feasible enterprise.

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